Analysis: Hydrothermal Activity at Yucca Mountain in light of thermal modeling and analog system observations by U.S. Geological Survey

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Executive Summary

[1] The term *hydrothermal activity* refers to the circulation of groundwaters with elevated temperatures through geological formations. Such circulation could compromise the integrity of a geological nuclear waste disposal system by initiating a plethora of processes, such as: - accelerated failure of waste canisters; - enhanced dissolution and transport of radionuclides; - development of *in situ* nuclear criticality; - creation of fast pathways toward the accessible environment; and many others. Hydrothermal activity is recognized as a safety and performance affecting process in most national programs dealing with disposal of high-level nuclear waste in geological formations.

[2] The discovery, in 1995-1998, of the fact that secondary minerals in the unsaturated zone of Yucca Mountain have been deposited as a result of circulation of thermal (up to 80-90°C) waters raised the possibility that hydrothermal activity could have occurred at Yucca Mountain in the past. In order to understand whether or not it represents a potential threat to the safety/performance of the planned nuclear waste disposal facility, it became incumbent on the planners to determine the origin of this circulation.

[3] In 2000, the USGS researchers working for DOE proposed a conceptual model which purportedly explained past elevated temperatures at Yucca Mountain without involvement of hydrothermal circulation. According to this model, the unsaturated zone has been conductively heated by a magma body emplaced 7-10 km to the north of Yucca Mountain.

[4] To verify the model, the USGS researchers attempted in 2001 to perform numerical modeling, but were unable to reproduce the empirical data (i.e., paleo-temperatures and ages) obtained from secondary minerals). Instead of acknowledging the failure of the modeling, they reported that results were in agreement with the empirical data. Assertions regarding the 'success' of modeling were repeatedly made by USGS researchers at different venues including peer-reviewed publications from 2001 through 2005. Technical documentation of simulations was not reported until as late as 2004, which precluded an independent technical evaluation.

[5] DOE promptly accepted the USGS 'conductive heating' model and included it in the Yucca Mountain Science and Engineering Report of 2001. The Report became a part of the package of technical documents that supported the decision of President Bush to recommend and the U.S. Congress to approve the Yucca Mountain site for development as a high level nuclear waste repository in 2002.

[6] In 2004, the purported success of the USGS simulations was used by DOE as a key argument to justify the exclusion of hydrothermal activity from consideration in the Total System Performance Assessment (TSPA) -- an instrument intended to evaluate compliance of the Yucca Mountain site with safety regulations.

[7] In response to a formal request submitted by NRC filed in 2001, some technical data pertaining to the 2001 USGS modeling were made public by a DOE contractor, Bechtel SAIC Company, LLC, in 2004. The data revealed that, contrary to the repeated assertions of the USGS researchers, both results of thermal simulations and observations on the natural analog system, Long Valley caldera in California, effectively refuted and rendered implausible the USGS 'conductive heating' model.

[8] It now appears that the recommendation of the President and the approval by the Congress of the Yucca Mountain site were based, at least in part, on untested scientific ideas which subsequently failed to pass the veracity test. The USGS researchers did not acknowledge in a timely manner the failure of their 2001 thermal simulations to corroborate the 'conductive heating' model. In turn, DOE uncritically accepted the faulty USGS model, making no attempts to verify it.

[9] Since the USGS 'conductive heating' model is demonstrably implausible, the exclusion of hydrothermal activity from consideration in the performance assessment of the proposed Yucca Mountain site does not appear to be justifiable. It is our opinion that adequate characterization of past hydrothermal activity at Yucca Mountain will raise formidable challenges to the viability of the site because of potential safety implications. Inclusion of hydrothermal activity as a potentially disruptive process (event) in the TSPA could effectively render the site non-licenseable for the purposes of nuclear waste disposal. Any performance assessment which does not consider this potentially disruptive process would be critically deficient.

1. Introduction: The Yucca Mountain thermal model

Volcanic tuffs in the thick unsaturated zone of Yucca Mountain, the site of the planned disposal facility for the nation's high-level nuclear waste, host ubiquitous secondary minerals. The minerals are hydrogenic, meaning that they were deposited from waters that circulated through the rock. They are interpreted by U.S. Geological Survey (USGS) researchers working for the U.S. DOE as having been deposited from rain waters that percolated from the surface deep into the mountain (Szabo and Kyser, 1990; Paces et al., 2001; Whelan et al., 2001; 2002). In 1998-2001, however, it was established that ancient waters responsible for the deposition of the minerals had temperatures up to 80-90°C. The temperatures were determined through studies of fluid inclusions by the independent work of three research groups representing the Russian Academy of Sciences (for the State of Nevada; Dublyansky, 1998; Dublyansky et al., 2001), USGS (Whelan et al., 2003), and the University of Nevada, Las Vegas (Wilson et al., 2003).

The determined temperatures are much higher than modern-day ambient temperatures, which in this part of the unsaturated zone do not exceed 25°C. In hydrogeology, the finding of waters with such temperatures would be considered a direct indication of **hydrothermal activity**. An important question arose: how to explain the circulation of these conspicuously thermal waters through the rock, which is believed to have remained some 200-300 m above the water table during the last 11.6 million years?

In 2000, the USGS researchers proposed a conceptual model which explained the elevated temperatures in the unsaturated zone of Yucca Mountain without the involvement of advective hydrothermal circulation (Marshall and Whelan, 2000). According to the model, the unsaturated zone was heated conductively by a magma body emplaced beneath the Timber Mountain caldera, approximately 7-9 km to the north of Yucca Mountain. Purportedly, the cooling of this magma body and the associated heating of the surrounding rocks continued for 5 to 8 million years. The USGS model is schematically presented in Fig. 1.

2. Significance of the USGS model for the Yucca Mountain Performance Assessment

One important feature of the USGS conceptual model is that it relates the past elevated temperatures in the unsaturated zone of Yucca Mountain to the large-scale silicic volcanism, which ceased in this part of Nevada between 9 and 11 million years ago. Regional tectonic conditions that led in the late Miocene to the development of this volcanism were not present in the area over the last several million years (Sawyer et al., 1994). Because of that fact, the likelihood of the recurrence of the caldera-scale volcanism is considered to be negligible. Therefore, if circulation of thermal waters through Yucca Mountain were to be demonstrated to be related to Miocene silicic volcanism, the recurrence of such circulation would also be considered unlikely. As a consequence, there would be no need to consider hydrothermal activity in the Performance Assessment of the Yucca Mountain repository.

Alternatively, if the temperatures measured in fluid inclusions were shown to reflect hydrothermal circulation unrelated to silicic volcanism, this would be of serious regulatory concern, and such circulation would have to be formally considered in the Yucca Mountain Performance Assessment.

3. Problems with documentation of the USGS thermal model

In 2001, the USGS researchers reported that they performed thermal simulations and the results "... *are in general agreement with paleotemperature data from fluid inclusions and isotopic compositions of secondary calcite at Yucca Mountain*" (Marshall and Whelan, 2001). The latter publication is a short abstract published in the proceedings of a scientific conference. The purported success of their simulation appeared to lend strong support to the USGS conceptual model but technical results of simulations were not reported, which precluded an independent technical evaluation.

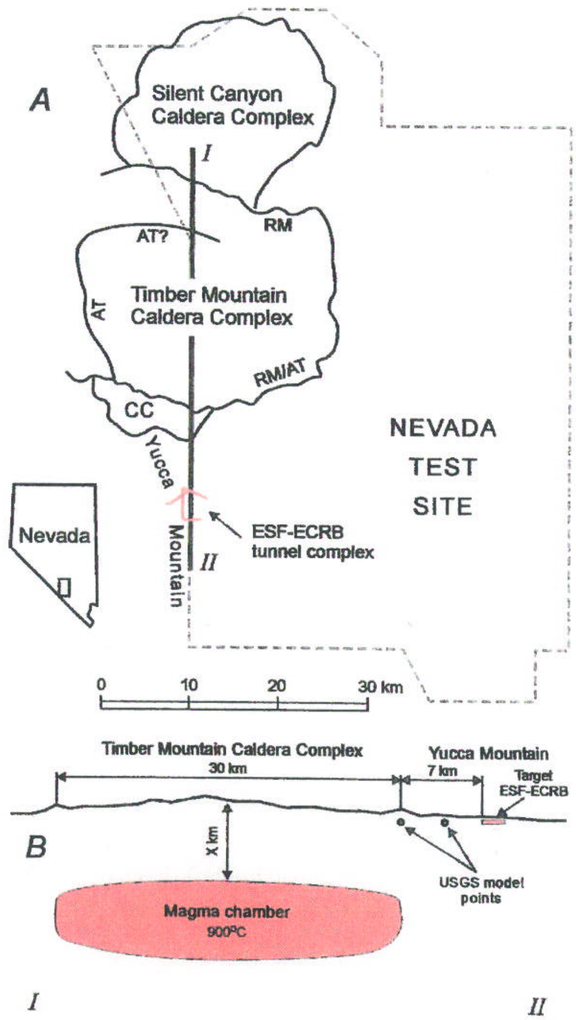

Fig. 1. Schematic presentation of the USGS thermal model.

A – Location map of the Timber Mountain caldera complex and the ESF-ECRB tunnel complex (where elevated fluid inclusion temperatures were measured) at Yucca Mountain. CC – segment of the Claim Canyon caldera (12.7-12.8 Ma); RM – boundary of the Rainier Mesa caldera (11.6 Ma); AT – boundary of the Ammonia Tanks caldera (11.45 Ma).

B – Schematic presentation of the USGS "conductive heating" model shown as a cross-section along the *I-II* line from *A*. Position of the ESF-ECRB tunnel complex is shown along with the points for which the USGS researchers simulated the time-temperature histories (depth from surface 250 m; Figure H-3 in BSC, 2004a).

The USGS model explains elevated temperatures at the ESF-ECRB by conductive heating of the rocks by a magma body emplaced beneath the Timber Mountain caldera complex.

Having analyzed the USGS conceptual model, the U.S. Nuclear Regulatory Commission (NRC) expressed skepticism regarding its viability:

> Speculation proposed by USGS researchers is that Yucca Mountain remained hot for many millions of years because of slow conductive cooling of magma chambers. Staff have previously commented that this conceptual model of slow cooling is unique and to date lacks adequate support. (NRC, 2005).

The lack of appropriate documentation prompted the NRC to request clarification from DOE on several aspects of the thermal modeling (NRC, 2001). Specifically, the NRC requested that DOE must: (1) document the results of the USGS conductive cooling model or provide an independent model that explains elevated temperatures in the unsaturated zone of Yucca Mountain; and (2) support the model by data from analog systems (e.g., young calderas where temperature profiles in boreholes would support conductive heating of the unsaturated zone for kilometers away from the eruption site).

DOE's response to the NRC request was published as Appendix H "Analog and Geochemical Evidence for Yucca Mountain Thermal-Hydrothermal History" to the Technical Basis Document No.2: Unsaturated Zone Flow (prepared by Bechtel SAIC Company LLC; BSC, 2004a). To our knowledge this is the only available publication to date in which technical details on the USGS thermal modeling are provided. In the following text we evaluate the status of the USGS modeling effort as presented in the aforementioned document.

4. Evaluation of the USGS thermal model

The purpose of the USGS simulations was to demonstrate that a magma body emplaced under the Timber Mountain Caldera some 7-9 km to the north of Yucca Mountain could heat, conductively, the rock of the Yucca Mountain unsaturated zone (Fig. 1) to the extent that temperatures measured in secondary minerals from the ESF-ECRB tunnel complex could be replicated. Simulations were carried out using the computer code HEAT (by K. Wohletz, Copyright

© 1998-2001, The Regents of the University of California). Modeling of geological systems always requires assumptions regarding some input parameters and conditions which are not known with certainty. Such parameters are typically constrained by bounding calculations. Other parameters cannot be changed because they define the "target function" which must be reproduced by the simulations. In the case of the USGS thermal model, the target function is defined by three sets of data: (1) the paleo-temperature (measured by fluid inclusions in minerals from the ESF-ECRB tunnel complex); (2) time (established by geochronological data; mostly U-Pb ages obtained for the minerals); and (3) geometry (the lateral distance between the magma chamber and the ESF-ECRB tunnel complex). The ability to reproduce the empirical data within the temperature-time-space coordinates is the central criterion based on which the success and the overall viability of the model will be judged.

4.1. Results of the simulations: No support to the USGS conceptual model

The aforementioned document (BSC, 2004a) demonstrates that the results of thermal simulations carried out by USGS researchers failed to reproduce the temperatures measured at Yucca Mountain. The results presented in Figs. 2 and 3 show that the matter concerns not just some minor discrepancy between the modeling results and the "target" data. It is apparent from the figures that the results of the USGS simulations are completely off the target. The simulations, therefore, <u>do not support</u> the USGS "magma cooling" model. The BSC (2004a) document states in this regard:

> Between 10 and 6 Ma, the magnitude and duration of heating predicted by these simulations are less than those recorded by fluid inclusion and stable isotopic data from secondary calcite from Yucca Mountain ... (p. H-11)

> The largest thermal perturbations are predicted for simulation 14, which includes a prolonged period of magmatism (15 to 11 Ma), the incorporation of a 500-m unsaturated-zone layer with a lower thermal conductivity, the presence of a 2-km thick convection system directly above the magma chamber, and a very shallow (2.5-km-deep) magma chamber. However, for this most extreme case, at 4 km distance from the edge of the magma chamber, a maximum temperature of less than 50°C is predicted, which declines to values less than 40°C at around 9 Ma. Even less heating would be predicted for most of the Yucca Mountain area, as the repository footprint lies approximately 4 to 9 km from the caldera margin. (p. H-10)

Importantly, as is apparent form Fig. 2, the USGS researchers modeled the temperatures at a distance 4 km away from the edge of the caldera, whereas the ESF-ECRB complex, where the target fluid inclusion temperatures were measured, is located 7 to 9 km from the Timber Mountain caldera (see Fig. 1). Therefore, the USGS simulations are non-representative in that they pertain to an area located 3 to 5 km closer to the magma body than the target area. At 7 to 9 km, the temperature increase would be substantially smaller, if perceptible at all.

The BSC (2004a) document plays down the failure of the USGS model to reproduce the target temperatures and times by pointing out that there exists an agreement between calculated and empirical data for the last 5 million years of the Yucca Mountain thermal history:

> The thermal model simulation results agree well with the mineralogic temperature record over the past 5 Ma. At 5 Ma, the estimated mineralogic temperatures for the Yucca Mountain area range from about 30°C to 40°C, and decline to values of around 20°C to 25°C over the past 0.5 Ma, similar to the thermal model simulation results for this time period. (p. H-11)

Although, technically speaking, the agreement does exist (in that the model curve intersects the field of the empirical data), this agreement is not meaningful. A line corresponding to a scenario in which there is no heating of rocks at all is shown in Fig. 3B. It is apparent that for the time interval from 5 to 0 million years ago, this hypothetical scenario agrees with the empirical data almost as well as the "best" USGS simulation, envisaging a continuous 4 million year-long heating of the shallow crust by a huge (30 km-wide, 7 km-thick) 900°C-magma body (simulation 14-4). The discrepancy between the two scenarios does not exceed 4°C – hardly a significant number for this type of simulations.

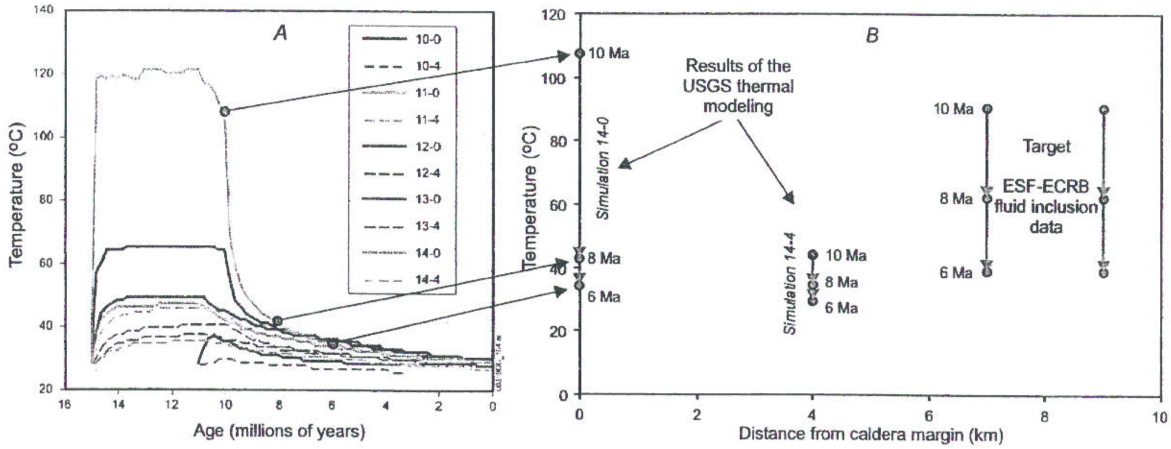

Fig. 2. Results of the USGS thermal simulations compared with the empirical temperature data from Yucca Mountain.

A – Thermal histories presented for five different simulations at a depth of 250 m and distances of 0 and 4 km from caldera margin (reproduced from Figure H-3 in BSC, 2004a). For the model curves, the first number is the simulation number, and the second number is the lateral distance away from the magma chamber margin, in km.

B - Comparison of the USGS simulation which produced the highest temperatures (simulation 14 in *A*) with the target fluid inclusion temperatures measured at the ESF-ECRB tunnel complex at Yucca Mountain (data from Figure H-4 in BSC, 2004a; see also Fig. 3 in this report). Temperatures calculated or inferred for 10, 8, and 6 million years ago (Ma) are shown by blue circles.

Note that the USGS thermal simulations failed to match the target temperatures.

In addition, a closer examination of the data presented in BSC (2004a) reveals that many input parameters used by the USGS researchers in their simulations were non-conservative and, in some instances, unrealistic. For example, the saturated-zone volcanic tuffs were assigned the very low value of thermal conductivity of 1.3 W/m°K (instead of the average 1.77 W/m°K reported for these rocks by Rautman and McKenna, 1997). Further, the USGS model included a 5 km-thick "insulating" layer of volcanic rocks (Table H-1 in BSC, 2004a), whereas geophysical studies by the USGS (Hildenbrand et al., 1999; Mankinen et al., 1999) show that the thickness of these rocks near Yucca Mountain rarely exceeds 1.5-2.0 km. Our calculations, employing the HEAT 3D code, showed that if more-realistic parameters are used, the calculated cooling times become shorter, by up to a factor of 2.

Further, the USGS researchers believed that their model was of a "... *disk-shaped magma chamber measuring 30 km in width (approximately the diameter of the Timber Mountain Caldera) and 7 km in height (corresponding to a volume of about 5,000 km^3)*". This is in error. The two-dimensional version of the HEAT code, used by the USGS researchers, in principle cannot model three-dimensional shapes. Important caveat is that the 2D thermal simulations yield cooling times which are overestimates relative to mathematically more realistic 3D simulations. This is explicitly stated in the program documentation: "*For 2D calculations the user should acknowledge that results will give longer cooling times because heat transfer in the third dimension is not calculated*" (HEAT 3D helpfile). For isometric magma bodies, the calculated 2D cooling times could be up to 30% longer that the more-realistic 3D cooling times.

4.2. Evidence from natural analog system: No support for the USGS conceptual model

In response to the NRC request, the DOE examined thermal data from an analog site, a 730,000 year-old Long Valley caldera complex in California in order to "... *determine whether cooling magmatic intrusions can provide a long-term (4 to 5 Ma) heat source for areas outside of the caldera margin...*" and "*...whether there is*

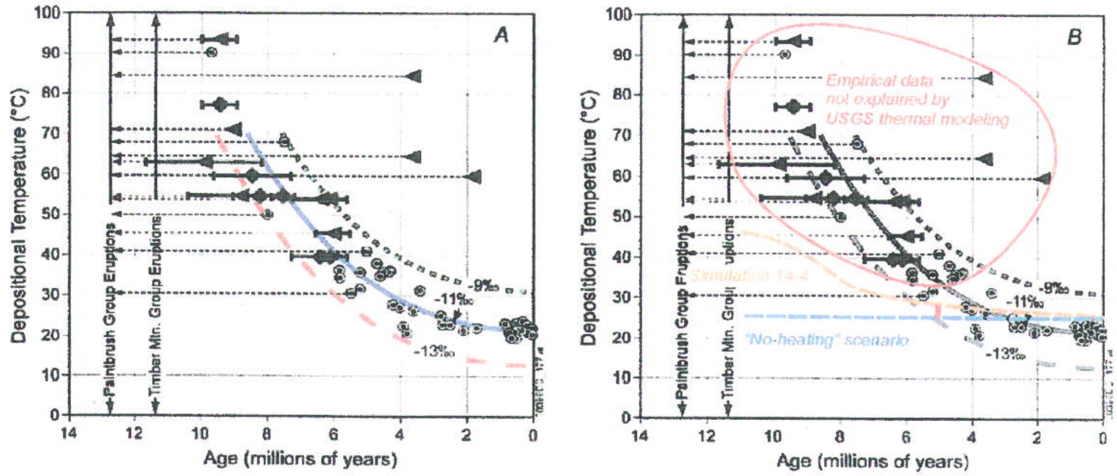

Fig. 3. Depositional temperatures and formation ages of secondary calcite from the ESF-ECRB tunnel complex compared with the results of the USGS thermal simulations.

A – Calcite depositional temperatures *vs.* formation ages (reproduced from Figure H-4 in BSC, 2004a). Calcite fluid inclusion homogenization temperatures that are tightly constrained by uranium-lead ages of secondary chalcedony/opal are plotted as black diamonds; those with only uranium-lead minimum age constraints are plotted as black triangles. Error bars indicate 2σ error of uranium-lead ages. Circled dots represent samples whose temperatures were calculated using oxygen isotopic ratios of calcite and whose ages are constrained by either uranium-lead or uranium-series age dates. Best-fit curves were calculated using calcite formation temperatures derived from calcite $\delta^{18}O$ values that formed from waters with $\delta^{18}O$ values of ~13‰ (red dashes), ~11‰ (solid blue), and ~9‰ (green dashes).

B – The "best" modeled temperature-time trajectory from the USGS simulation 14-4 (re-plotted from Figure H-3 in BSC, 2004a; see also Fig. 2 in this report) is shown as an orange dashed line. The blue dashed line represents a scenario in which there is no heating of the rocks. The vertical red bar shows the discrepancy between these hypothetical scenarios at 5 Ma.

Note that: (a) out of all simulations reported in BSC (2004a), simulation 14-4 returned the highest temperatures; (b) simulation 14-4 calculates temperatures at 4 km from the caldera margin, whereas depositional temperatures shown on the graph were measured at 7 to 9 km from the caldera; (c) nevertheless, the simulation failed to match the measured temperatures; and (d) for the last 5 million years, the maximum difference between the simulation 14-4 (envisaging continuous heating of the rocks by a 900°C-magma body during 4 million years) and the "no heating" scenario is as small as 4°C, while the error of the USGS paleo temperature estimates is *ca.* ±10°C.

evidence for elevated temperatures comparable to those recorded by the secondary minerals at Yucca Mountain outside of the caldera margins for these systems" (BSC, 2004a, p. H-19). This turned out to be yet another test that the USGS thermal model failed (Fig. 4). The document concludes:

> While elevated subsurface temperatures have been encountered within the Long Valley caldera, there is little evidence for significant heating outside of the caldera margin. (p. H-20)

> ...a thermal anomaly outside of the Long Valley caldera would not be detectable 700,000 years after the last major phase of magmatic activity. Continued volcanism after the eruption of the Bishop Tuff 730,000 years ago has helped to sustain the active hydrothermal system within the caldera but has not had a significant impact on the thermal regime outside of the caldera ... (p. H-21)

Again, the BSC (2004a) document emphasizes the consistency between the USGS modeling results and the Long Valley thermal data:

> The Long Valley analog is consistent with the thermal modeling results of Marshall and Whelan (2001) for the Timber Mountain volcanic center. In the Marshall and Whelan model (Figure H-5), shallow heating in the subsurface is focused primarily in the area directly above the caldera, and temperatures

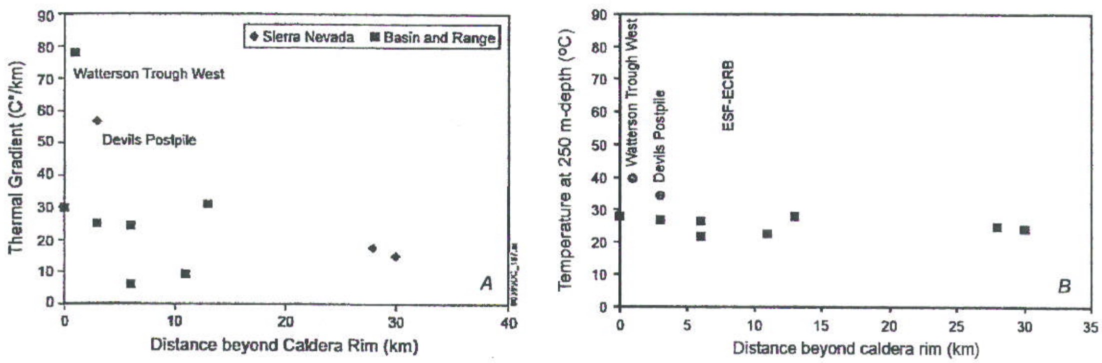

Fig. 4. Thermal data from natural analog site – the Long Valley caldera, formed 730,000 years ago.

A – Measured thermal gradients *vs.* distance outside the caldera margin for wells around the Long Valley caldera (reproduced from Figure H-11, BSC, 2004a);

B - Temperatures at a depth of 250 m from surface. The temperatures were calculated from thermal gradients shown in *A* assuming surface temperature of 20°C. The fluid inclusion temperatures from Yucca Mountain (box ESF-ECRB) are shown for comparison. Red circles show abnormally high temperatures related to hydrothermal circulation (Watterson Trough West) and recent magmatic intrusion (Devils Postpile).

Note that 0.7 Ma after eruption of the Long Valley volcanic system, the rocks surrounding the caldera do not exhibit any traces of thermal disturbance. The Long Valley subsurface temperatures are much lower than the temperatures measured in secondary minerals at Yucca Mountain. According to the USGS, the latter temperatures existed over the time span of 1.5 to 5.5 Ma after the Timber Mountain eruption (see Figure H-4 in BSC, 2004a and Fig. 3 in this report).

> decline quickly away from the caldera margin. (p. H-21)

This is a correct observation: both USGS thermal simulations and observations at Long Valley caldera are consistent in showing that the elevated temperatures measured in the ESF-ECRB tunnel complex at Yucca Mountain, 7 to 9 km away from the Timber Mountain caldera rim, cannot be explained by the conductive heat transfer from a magma body residing under this caldera.

5. Could the USGS thermal model be salvaged?

DOE postulated a number of mechanisms that could potentially be invoked to resolve the discrepancy between the USGS simulations and the empirical data:

> Possible scenarios that might resolve this discrepancy include: (1) continued injection of magma (without associated volcanic activity) into the shallow crust in the vicinity of the Timber Mountain volcanic center after 11 Ma, (2) intrusion of magma closer to Yucca Mountain area (to the southeast of the Timber Mountain caldera), (3) lateral subsurface flow of hydrothermal fluids from the Timber Mountain area toward Yucca Mountain, and (4) the presence of additional overburden in the Yucca Mountain area that was subsequently removed by uplift and erosion, which would have resulted in a deeper and hotter environment for the earlier portion of the thermal history of this area. (BSC, 2004a, p. H-19)

Whether or not these hypothetical scenarios could, indeed, eliminate the discrepancy cannot be known with certainty without quantitative modeling and subsequent validation of the model's boundary conditions and input parameters. It should be noted, however, that the acceptance of any of the scenarios proposed above would necessarily lead to the need for a serious reevaluation of the current understanding of the geological system of Yucca Mountain, an understanding based on more than 20 years of research. Brief comments on the specific proposed scenarios follow.

Continued injection of magma, including injections close to Yucca Mountain. The climactic Timber Mountain eruptions rank among the 15 most voluminous volcanic eruptions known on Earth (Mason et al., 2004). Therefore, the magma chambers modeled by the USGS researchers should be viewed as the "upper bound" estimate of the magma volumes that could have been involved in the heating of the Earth's crust in the area. After the Timber Mountain eruptions volcanic activity began to wane, centers of eruptions moved in a northwesterly direction (the youngest Stonewall Mountain volcanic center is located *ca.* 70 km away from Timber Mountain). It is highly unlikely therefore that a magma body emplaced subsequent to the Timber Mountain magma chambers could have produced heating more significant than that associated with the climactic stage of volcanic activity.

In theory, some heating of the crust could have been associated with intrusion of unknown magma bodies that did not reveal themselves through volcanic eruptions. The USGS thermal modeling results indicate that in order to exert any sizable influence on the thermal regime in the ESF-ECRB vicinity of Yucca Mountain, such intrusions would have to be: (a) of large sizes; and (b) emplaced very close to the target block, i.e., to the south of the Timber Mountain complex. To the best of our knowledge, no such intrusive body has been identified in the vicinity of Yucca Mountain to date. The NRC analysis adopted a similar conclusion:

> There is little evidence to support DOE's scenario of sustained magmatism and, thus, sustained heating of crustal rocks within the Timber Mountain caldera after 11 million years. ... DOE does not cite any information to support the scenario of a hidden magmatic intrusion occurring south of the Timber Mountain or Claim Canyon caldera boundaries. Features characteristic of a significant subsurface intrusion, such as large, coherent gravity or magnetic anomalies, are not found in available data (Ponce, et al., 2001; Ponce and Blakely, 2001). (NRC, 2005, p. 16).

In any case, before the USGS conjecture regarding sustained crustal heating could be accepted, such magma body or bodies would need to be identified, their locations, sizes and time of intrusion would have to be determined, the thermal effect would have to be modeled, and the results of such modeling would have to be verified by geologic and geophysical research.

Lateral subsurface flow from the Timber Mountain area toward Yucca Mountain. The accepted understanding is that the unsaturated zone at Yucca Mountain formed shortly after the development of the mountain *ca.* 11.6 million years ago, and have persisted since that time until the present (DOE, 2001). The vitric tuffs of the thick unsaturated zone at Yucca Mountain do not exhibit devitrification or pervasive alteration, as would be expected if heated waters moved through the rocks for any extended period of time, particularly for several millions of years. This means that a path of the "lateral subsurface flow" of thermal waters from Timber Mountain proposed in BSC (2004a) could not have been directly <u>through</u> the unsaturated zone of Yucca Mountain. It could only have occurred through the underlying saturated zone; heating of the rocks in the unsaturated zone above would still have to be by conductance.

The lateral outflow of thermal waters, the so-called Timber Mountain caldera hydrothermal event, is known to have occurred between 10.5 to 11.0 million years ago (Bish and Aronson, 1993). In the Yucca Mountain area, it affected only deep (below *ca.* 1000 m) parts of the geologic section. Mineralogical evidence and thermal calculations indicate that this hydrothermal system could not have caused heating of the unsaturated zone at the ESF level commensurate with the fluid inclusion temperatures (Szymanski et al., 2000). This subject will be discussed in more detail below.

The presence of additional overburden. The long-term (Quaternary) erosion rate at Yucca Mountain is believed to be low compared with other areas within the United States, averaging 0.2 cm per thousand years (YMP, 1993). It is thought that no more than *ca.* 100 m of the overburden have been removed from Yucca Mountain over the last 10 million years (e.g., U.S. DOE, 1998). This overburden was (implicitly) accounted for in the USGS simulations, which calculate the temperatures at a 250 m-depth, whereas the ESF-ECRB minerals that yielded the highest homogenization temperatures (>70°C) were collected from depths of 30 to 80 m.

Apparently, in order to significantly change the results of the thermal simulations, the amount of overburden (and the long-term erosion rate) would have to be assumed to be large. Because potential erosion at the Yucca Mountain site is a regulatory concern, acceptance of the DOE "additional overburden" concept would require serious revision of the current understanding of the erosion rates at Yucca Mountain.

6. "Advertising" the USGS thermal model

The "conductive heating" model was introduced by the USGS researchers in 2000 and 2001 in two short abstracts of the Geological Society of America annual meetings. Both abstracts mention thermal modeling and assert that the results of simulations are in agreement with the empirical thermometric and age data obtained from secondary minerals at Yucca Mountain:

> …this trend indicates a gradual cooling of the rocks over millions of years, in agreement with thermal modeling of magma beneath the 12-Ma Timber Mountain caldera just north of Yucca Mountain. This model predicts that temperatures significantly exceeding current geotherm values occurred prior to 6 Ma. (Marshall and Whelan, 2000, p. A-259)

> … the simulations indicate that modern geothermal gradients were reached at 6 Ma to 3 Ma. These results are in general agreement with paleotemperature data from fluid inclusions and isotopic compositions of secondary calcite at Yucca Mountain. (Marshall and Whelan, 2001, p. A-375)

Presenting USGS results at the U.S. Nuclear Waste Technical Review Board Meeting in May 2001, Joseph Whelan again asserted that their thermal simulations were successful:

> So, to conclude, both fluid inclusions and calcite delta O-18 indicate elevated temperatures during the early and intermediate stages of calcite formation. Those temperatures are consistent with a likely thermal history of the unsaturated zone tuffs as indicated by the age constraint temperature data and by thermal modeling. (NWTRB, 2001, p. 151)

The foregoing discussion, however, demonstrates that, contrary to these repeated assertions, simulations carried out by USGS researchers in 2001 failed to reproduce both the target temperatures and the target times. The BSC (2004a) document states this explicitly:

> Marshall and Whelan (2001) concluded that the presence of a long-lived magma chamber at the Timber Mountain volcanic center could account for elevated thermal conditions in the vicinity of the repository up to around 6 Ma.

> However, closer evaluation of the model results depicted in Figure H-3 indicate that the magmatic activity at Timber Mountain as represented by these simulations would only produce minor and relatively short-lived thermal perturbations for the Yucca Mountain area. (p. H-9-H-10).

Despite the failure of the simulations, between 2001 and 2005, the USGS researchers continued to publicize their "conductive heating" model by repeating assertions regarding the success of thermal modeling at various venues (Fig. 5), including published assertions in peer-reviewed journal articles:

> Warmer depositional temperatures in the past reflect the prolonged thermal input to the UZ from the ongoing regional magmatic activity … Yucca Mountain tuffs were erupted between 15 and 11 Ma (Sawyer, et al. 1994) from large caldera complexes only ~10 km to the north. Simulations indicate that these Miocene magma chambers would have disturbed local heat-flow regimes on the multi-million-year time scales producing elevated UZ temperatures to 6 Ma or younger (Marshall and Whelan, 2000, 2001; Whelan et al., 2001). (Whelan et al. 2002, pp. 746-747)

> Simulations of temperatures in the upper crust around a large intrusive heat source to the north indicated that cooling of the UZ at Yucca Mountain could have taken until 4-6 Ma, which is consistent with the fluid inclusion thermochronology … (Whelan et al., 2004, p. 1884)

> These highest temperatures of deposition are explained in Marshall and Whelan (2001) with a thermal model … that links the slow cooling of the UZ at Yucca Mountain to the cooling magma body beneath the Timber Mountain caldera complex. … The driving mechanism is dissipation of a large amount of thermal energy emplaced at shallow crustal levels via

magmatic processes. (Marshall et al., 2005, p. 221)

Tellingly, all these publications cite the abstract of Marshall and Whelan (2001) as the key reference. There are no indications of newer modeling results[1].

7. Acceptance of the USGS thermal model

7.1. Acceptance by U.S. DOE

Despite the lack of documentation and validation of the USGS thermal model, it was hastily accepted by the DOE in 2001 and included in the Yucca Mountain Science and Engineering Report. In the latter document, the elevated temperatures measured in fluid inclusions were dismissed by relating them to "... *a well-documented thermal period that affected the volcanic rock for a long time after its formation*" (DOE, 2001, p. 4-402). The Report was used in the process of recommending the Yucca Mountain site to President Bush, who accepted the recommendation and sent it on to the Congress. The Congressional resolution approving the President's recommendation was signed into law in June 2002. As was discussed above, it is now clear that the results available in 2001 simply did not support the USGS model; they actually refuted it.

When technical data on the USGS modeling were published by the DOE contractor (BSC, 2004a) the flawed character of the USGS model become apparent. Amazingly, despite the problems discussed in previous sections, the document offered the following overall conclusion regarding the USGS model:

> In summary, while the thermal model simulations of Marshall and Whelan (2001, 2004) do not predict a thermal event that is as prolonged and pronounced as that recorded by secondary minerals at Yucca Mountain, their general model provides a mechanism to account for the presence of elevated temperatures between 10 and 6 Ma. (p. H-12)

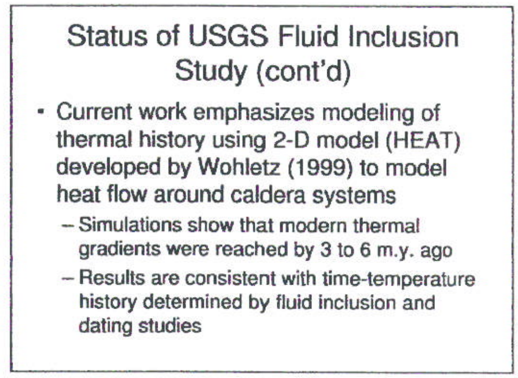

Fig. 5. Status of the thermal modeling by USGS as presented at one of the public meetings in 2001. Downloaded from the NRC's Licensing Support Network (http://www.lsnnet.gov/). Dated 08/31/2001.

The latter statement does not appear to be a sound scientific judgment. It is hard to comprehend how a model which so utterly failed to reproduce the target temperatures and target times (see Figs. 2 and 3), "provides a mechanism" to account for these temperatures and times.

Bechtel SAIC's acceptance notwithstanding, the response to critical flaws of the model appears to follow a pattern with DOE and its contractors. In a recent Analysis Model report discussing features, events, and processes to be considered in the Yucca Mountain Total System Performance Assessment for License Application, the purported success of the USGS thermal modeling and the "support" from analog observations was used as a key argument, to base the exclusion of hydrothermal activity from consideration in the TSPA-LA (BSC, 2004b).

7.2. Acceptance by U.S. NRC

The NRC staff reviewed Appendix H of the BSC (2004a) document. The review (NRC, 2005, at pp. 12-18) states:

> Additional thermal modeling by Marshall and Whelan (2001) suggests that the long-lived, near-surface thermal perturbation at Yucca Mountain could not be reproduced by their thermal models, which predicted much faster cooling than inferred from oxygen and strontium isotope analyses in secondary minerals... (p. 15).

The NRC review cites the four hypothetical mechanisms proposed in BSC (2004a) to explain

[1] The BSC (2004a) contains one reference to a 2004 publication (Marshall and Whelan, 2004). The later publications, however, is a poster presented at the 2001 Meeting of the American Geophysical Union.

elevated temperatures at Yucca Mountain (i.e., sustained magmatism; magmatic intrusions outside the caldera; additional overburden; and lateral outflow of hydrothermal fluids). The NRC was explicit in stating that none of these hypothetical mechanisms is supported by factual evidence:

> There is little evidence to support DOE's scenario of sustained magmatism and, thus, sustained heating of crustal rocks within the Timber Mountain caldera...
>
> DOE does not cite any information to support the scenario of a hidden magmatic intrusion occurring south of the Timber Mountain or Claim Canyon caldera boundaries.
>
> ... DOE does not provide a technical basis to account for the thickness of potentially missing deposits needed for this scenario. In addition, DOE does not discuss how much additional burial would be needed in this scenario to account for paleotemperatures measured in 6 to 11 million year minerals at Yucca Mountain.
>
> ... DOE does not present a model for advective hydrothermal flow from the cooling Timber Mountain caldera... (NRC 2005, pp. 16-17).

The NRC review rejects the first three mechanisms proposed by DOE, but does accept the fourth: "*Subsurface outflow of hydrothermal fluids from the Timber Mountain caldera system, however, appears a credible scenario to account for elevated paleotemperatures preserved in 6 to 11 million year minerals at Yucca Mountain*" (NRC 2005, p.17). Astonishingly, the only argument put forth by the NRC to justify this acceptance was a vague statement that: "*... such flows are commonly observed in geothermal systems that occur above and adjacent to large-volume magma bodies (e.g., Goff et al., 1988)*" (Ibid, p. 17).

The reason why the NRC reviewers decided to cite general observations on geothermal systems, ignoring the substantial body of site-specific information in this regard, remains a mystery to us. There is little doubt that if the site-specific information were used, this hypothetical mechanism would also have to be rejected.

The southward flowing hydrothermal system is known to have existed at Timber Mountain 10-11.5 million years ago. It was related to a large silicic magma body emplaced beneath the Timber Mountain caldera after the latest climactic eruption of 11.45 Ma, which precisely corresponds to the DOE thermal model. The results of studies of this hydrothermal system are documented in a number of publications (e.g., Spengler et al., 1981, Caporuscio et al., 1982, Bish, 1989, Bish and Aronson, 1993, and Weiss et al., 1994). For example, the latter publication reported radiometric ages of alteration minerals and concluded that they are

> ... consistent with alteration coeval with post-collapse volcanism and magmatic activity of the Timber Mountain II caldera to the north. These ages are 1.7 to 2.7 million years younger than the youngest altered unit and therefore cannot reflect diagenetic or deuteric water-rock interaction during cooling of the host units ... Taken together, the age data, mineralogy and textural features are best interpreted as the result of a large, south-flowing hydrothermal system driven by heat from magmatic activity in the nearby Timber Mountain caldera system. (Weiss et al., 1994, p. 23).

According to Bish and Aronson (1993) the system included an upflow zone in the area of the Claim Canyon cauldron, where thermal waters likely discharged at the surface (Fig. 6). Further to the south they affected only deep parts of the rock sequence (at Yucca Mountain – at a depth of *ca.* 1000 m and deeper). In other words, thermal waters <u>did not flow through the unsaturated zone-rocks</u> of Yucca Mountain, where minerals that provided the fluid inclusion record of elevated temperatures are located. Bish and Aronson (1993) noted a pronounced asymmetry of the hydrothermal system: "*...it is apparent that a significant thermal event has occurred in the northern end of Yucca Mountain but has not significantly affected the southern end*" (p. 153) and suggested that the rocks of the unsaturated zone were efficiently cooled by a "rain curtain" effect.

It is apparent from Fig. 6 that temperatures of 75-90°C at the ESF-ECRB level could not have been caused by the Timber Mountain caldera hydrothermal fluids that circulated some 700-900 m deeper.

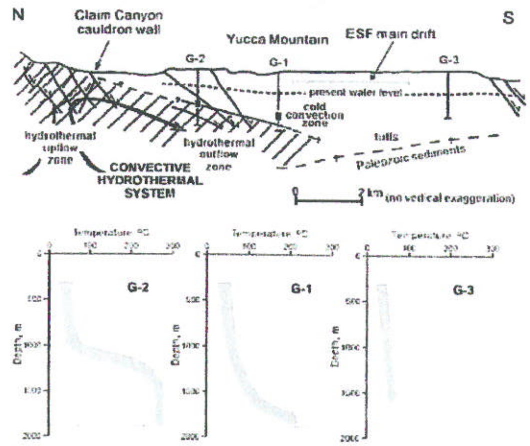

Fig. 6. Reconstruction of the Timber Mountain advective hydrothermal circulation system near Yucca Mountain 10-11.5 Ma ago and schematic temperature profiles for boreholes USW G-1, G-2 and G-3 estimated from illite/smectite mineralogy and fluid inclusion data (compiled from Bish and Aronson, 1993). Black rectangles on boreholes G-2 and G-1 on the upper plate indicate approximate depth at which the temperature of 100°C was reached during this hydrothermal event.

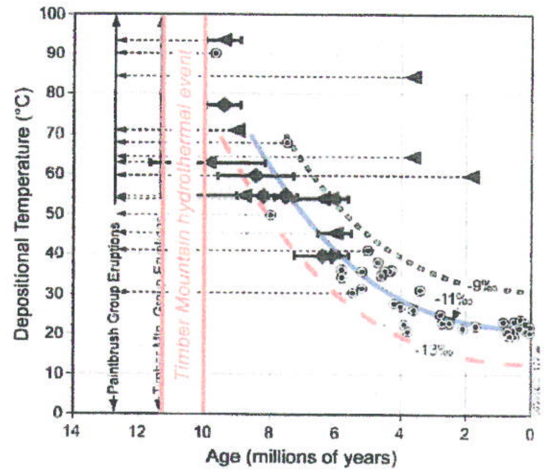

Fig. 7. Time of operation of the Timber Mountain caldera hydrothermal system (red lines; based on the data of Bish and Aronson, 1993) compared with the depositional temperatures and formation ages of secondary calcite from ESF-ECRB tunnel complex (reproduced from Figure H-4 in BSC, 2004a).

Another constraint is provided by time. A hydrothermal system, such as the Timber Mountain one, can only be active as long as the source of heat (magma body) is present. From the shape of the USGS model curves shown in Fig. 2A it is apparent that even large magma bodies cool down fairly rapidly, over 1.5 to 2 million years, so that the heat source that fuels convection exhausts itself within this time frame. On the basis of the studies of the ages of alteration minerals, Bish and Aronson (1993) concluded that the Timber Mountain caldera hydrothermal system was active between 11.5 and 10 million years ago *circa* and that "*...no hydrothermal alteration has occurred since the waning of Timber Mountain volcanism about 10 my ago.*" (p. 159). As is shown in Fig. 7, the Timber Mountain caldera hydrothermal event ended well before the time when, according to the USGS age data, the elevated-temperature secondary minerals from the ESF-ECRB tunnel complex were deposited. Thus, the acceptance, by NRC, of the DOE hypothetical explanation invoking lateral flow of thermal waters does not appear to have a sound scientific basis.

Acceptance of the "lateral flow" hypothesis, however, allowed NRC to accept the USGS thermal model as a whole:

> Although studies of secondary minerals at Yucca Mountain by several organizations continue to this date, the NRC staff consider the conceptual model proposed by DOE for secondary mineral deposition at Yucca Mountain is generally consistent with available lines of evidence, notwithstanding remaining uncertainties in the age, timing, and origin [*sic! YD*] of the thermal perturbations that produced elevated temperatures evidenced by fluid inclusions... (NRC, 2005, p-17)

In view of the discussion above, this NRC conclusion does not seem to be scientifically defensible.

8. Summary of findings

1. Secondary minerals found in the unsaturated-zone tuffs of Yucca Mountain provide unequivocal evidence that thermal waters (up to 70-90°C) circulated through this zone in the past.

2. The USGS phenomenological model, attributing elevated temperatures measured in the Yucca Mountain secondary minerals to conductive heating caused by a large-scale magma body is the only model which relates the later minerals with the late Miocene silicic volcanism. Since recurrence of silicic volcanism in the future is improbable, this model, if it were proven correct, would render thermal waters that deposited secondary minerals at Yucca Mountain inconsequential from the standpoint of the safety and performance of the planned nuclear waste disposal facility.

3. Thermal simulations performed by USGS researchers in 2001 to verify their phenomenological model, and observations on the analog Long Valley caldera system effectively refuted the original USGS thermal model. The only conclusion that could reasonably be drawn from the analysis of simulation results and analog observations reported in BSC (2004a) is that the elevated temperatures at Yucca Mountain cannot be explained by heat transfer from any magma chamber known in the vicinity of Yucca Mountain under any geologically plausible scenario.

4. In 2000, the USGS thermal model had not yet been supported by thermal simulations, whereas simulations performed in 2001 demonstrated that the model was not viable. Nevertheless, the USGS model was accepted by the DOE in 2001 and become a part of the package of technical documents that eventually led President Bush to recommend and the U.S. Congress to approve the Yucca Mountain site for further development as a high level nuclear waste repository. It now appears that both the recommendation of the President and the approval of the Congress were based, at least in part, on untested scientific ideas which failed to pass the veracity test.

5. The USGS researchers did not acknowledge in a timely manner the failure of their thermal simulations to reproduce the temperatures measured in the Yucca Mountain secondary minerals. Instead, in publications from 2001 through 2005, they asserted that simulations successfully reproduced the temperature-time relationships determined from the minerals. These claims are demonstrably untrue.

6. In a 2004 technical document the DOE disclosed the unsuccessful results of the USGS thermal simulations, and postulated as many as four hypothetical mechanisms, which could have decreased or removed the discrepancy between the USGS simulations and the thermal record obtained from secondary minerals at Yucca Mountain (BSC, 2004a). None of the proposed mechanisms was supported in the document by factual evidence. Despite the apparent lack of a sound technical basis, introduction of these conjectures allowed the DOE to maintain that the USGS thermal model was generally sound.

7. The NRC staff opined that one of the DOE-postulated mechanisms (subsurface lateral flow of thermal waters from Timber Mountain caldera) represents a credible scenario to account for elevated temperatures at Yucca Mountain (NRC, 2005). This allowed the NRC to accept the DOE conceptual model as an explanation of the secondary mineral deposition. The NRC opinion ignores available evidence showing that the lateral flow of thermal waters from the Timber Mountain caldera toward Yucca Mountain has existed but did not cause any discernible thermal effects in the unsaturated-zone rocks at Yucca Mountain.

9. Concluding remarks

Hydrothermal activity as a feature, event, or process (FEP) has been excluded, by DOE, from the Total System Performance Assessment for License Application for the proposed Yucca Mountain nuclear waste repository (BSC, 2004b). The exclusion was based, in large part, on the misrepresented results of the USGS thermal simulations and analog observations. These results were portrayed as providing solid confirmation of the USGS conceptual model.

The analysis presented above shows that the results of the USGS modeling and analog observations, in fact, disprove this model. The genetic link between thermal waters in the unsaturated zone of Yucca Mountain and the Miocene silicic magmatism cannot be established. This means that in spite of years of research, DOE presently does not have a plausible explanation for past circulation of waters with elevated, hydrothermal temperatures through the unsaturated zone of Yucca Mountain.

Hydrothermal activity is a process that could seriously compromise performance and safety of the nuclear waste disposal facility. The question becomes: Can a potentially disruptive process, for which adequate understanding is lacking and a defensible model is not proposed, be excluded from consideration in the performance assessment of the nuclear waste disposal facility?

Our strong opinion is – it cannot. The appropriately defined FEP Hydrothermal Activity must be reinstated. A defensible phenomenological model must be proposed to explain the origin of the past hydrothermal circulation at Yucca Mountain. The model must be validated and included in TSPA-LA calculations. Any assessment of the expected performance and safety for the proposed repository at Yucca Mountain which does not consider this potentially disruptive process would be critically deficient.

Appendix

Below is a copy of an e-mail message downloaded from the NRC's Licensing Support Network (http://www.lsnnet.gov/).

```
Author: Jim Houseworth
Organization: RWDOE
From: CN=Jim Houseworth/OU=YM/O=RWDOE
PostedDate: 07/08/2003 07:55:26 PM
SendTo: Joe Wang
CopyTo:
ReplyTo:
BlindCopyTo:
Subject: Thermal historoy model
Body: Joe,

I just was going thorugh FEPs and we have the one on hydrothermal activity.
This is the FEP that NRC wants us to exclude based on the thermal history model
and its consitency with secondary minerals and fluid inclusions evidence.
What's the latest on this modeling effort?

Jim
```

Note: J.E. Houseworth has been a Responsible Manager/Lead in preparation of the analysis/model report: Features, Events, and Processes in UZ Flow and Transport (BSC, 2004b). The latter document, published in November 2004, excludes the Hydrothermal Activity FEP from the Total System Performance Assessment for License Application.

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