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TRANSMITTAL OF APPENDIX H, *TECHNICAL BASIS DOCUMENT NO.2: UNSATURATED ZONE FLOW* ADDRESSING KEY TECHNICAL ISSUE (KTI) AGREEMENTS EVOLUTION OF THE NEAR-FIELD ENVIRONMENT (ENFE) 2.03 AND TOTAL SYSTEM PERFORMANCE ASSESSMENT AND INTEGRATION (TSPAI) 2.02, COMMENTS 3, 4, 12, AND J-23

Reference: Ltr, Ziegler to Director, Division of High-Level Waste Repository Safety, dtd 5/28/04 (Transmittal of TBD No. 2: Unsaturated Zone Flow, Revision 1)

This letter transmits Appendix H of *Technical Basis Document No. 2: Unsaturated Zone Flow*. This Technical Basis Document contains a summary of the current conceptual understanding of flow in the unsaturated zone and provides the context within which individual KTI agreements related to flow in the unsaturated zone are addressed. Appendices A through G of the Technical Basis Document were submitted with the referenced letter. The final appendix, I, will be transmitted under separate cover.

Appendix H, *Analog and Geochemical Evidence for Yucca Mountain Thermal-Hydrothermal History*, Revision 1, (enclosure) provides a direct response to KTI agreements ENFE 2.03 and TSPAI 2.02, Comments 3, 4, 12, and J-23. This appendix provides documentation of the technical basis for excluding the process of hydrothermal activity from consideration in the total system performance assessment for the License Application.

The U.S. Department of Energy considers ENFE 2.03 and TSPAI 2.02, Comments 3, 4, 12, and J-23, to be fully covered in Appendix H of *Technical Basis Report 2: Unsaturated Zone Flow*, and pending review and acceptance by the U.S. Nuclear Regulatory Commission, these agreements should be closed.

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There are no new regulatory commitments in the body or the enclosure to this letter. Please direct any questions concerning this letter and its enclosures to Joe C. Price at (702) 794-1441 or email joe_price@ymp.gov, or Eric T. Smistad at (702) 794-5073 or email eric_smistad@ymp.gov.

Joseph D. Ziegler, Director
Office of License Application and Strategy

OLA&S:JCP-1386

Enclosure:
Appendix H, Analog and Geochemical Evidence for Yucca Mountain Thermal-Hydrothermal History, Revision 1

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APPENDIX H

ANALOG AND GEOCHEMICAL EVIDENCE FOR YUCCA MOUNTAIN THERMAL–HYDROTHERMAL HISTORY (RESPONSE TO ENFE 2.03 AND TSPAI 2.02 (COMMENTS 3, 4, 12, AND J-23))

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application (LA) as the approved analyses of record at the time of LA submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

APPENDIX H

ANALOG AND GEOCHEMICAL EVIDENCE FOR YUCCA MOUNTAIN THERMAL–HYDROTHERMAL HISTORY (RESPONSE TO ENFE 2.03 AND TSPAI 2.02 (COMMENTS 3, 4, 12, AND J-23))

This appendix provides a response to Key Technical Issue (KTI) agreement Evolution of Near-Field Environment (ENFE) 2.03 and Total System Performance Assessment and Integration (TSPAI) 2.02 (Comments 3, 4, 12, and J-23). These agreements relate to the technical basis for excluding features, events, and processes (FEP) 1.2.06.00.00 for hydrothermal activity from total system performance assessment for the license application.

H.1 KEY TECHNICAL ISSUE AGREEMENT

H.1.1 ENFE 2.03 and TSPAI 2.02 (Comments 3, 4, 12, and J-23)

Agreement ENFE 2.03 was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on ENFE held January 9 to 12, 2001, in Pleasanton, California (Reamer 2001a). ENFE Subissues 1, 2, 3, and 4, were discussed at that meeting. ENFE 2.03 was discussed under Subissue 2, Coupled Thermal-Hydrologic-Geochemical Effects on Waste Package Environment.

Agreement TSPAI 2.02 (Comments 3, 4, 12, and J-23) was reached during the NRC/DOE Technical Exchange and Management Meeting on TSPAI and FEPs held August 6 to 10, 2001, in Las Vegas, Nevada (Reamer 2001b). TSPAI Subissues 1, 2, 3, and 4 were discussed at that meeting. TSPAI 2.02 was discussed under Subissue 2, Scenario Analyses.

The wording of the agreements is as follows:

ENFE 2.03

> Provide the technical basis for FEP 1.2.06.00 (Hydrothermal Activity), addressing points (a) through (e) of NRC Subissue 2 slide handed out at the January 2001 ENFE technical exchange. The DOE will provide additional technical bases for the screening of FEP 1.2.06.00 (Hydrothermal Activity), in a future revision of the *Features, Events, and Processes in UZ Flow and Transport* AMR (ANL-NBS-MD-000001), expected to be available in FY 02. Within these technical bases, the DOE will address NRC comments [points (a) through (e)] presented on the NRC Subissue 2 slide handed out at the January 2001 ENFE technical exchange or provide justification that it is not needed.

TSPAI 2.02 (Comments 3, 4, 12, and J-23)

> Provide the technical basis for the screening argument, as summarized in Attachment 2. See Comment # 3, 4, 11, 12, 19 (Parts 1, 2, and 6), 25, 26, 29, 34, 35, 36, 37, 38, 39, 42, 43, 44, 48, 49, 51, 54, 55, 56, 57, 59, 60, 61, 62, 63, 64, 65, 66, 68, 69, 70, 78, 79, J-1, J-2, J-3, J-4, J-7, J-8, J-9, J-10, J-11, J-12, J-13, J-14, J-15, J-17, J-20, J-21, J-22, J-23, J-24, J-25, J-26, and J-27. DOE will provide the

technical basis for the screening argument, as summarized in Attachment 2, for the highlighted FEPs. The technical basis will be provided in the referenced FEPs AMR and will be provided to the NRC in FY03.

The NRC slide presented at the January 2001 Technical Exchange on ENFE (NRC 2001) proposed that the DOE strengthen the technical basis for excluding FEP 1.2.06.00.00 for hydrothermal activity and recommended (in points (A) through (E)) that DOE:

(A) Document the results (conductive cooling model of Timber Mountain Caldera magma body) presented by Brian Marshall at Summit 2000 Geological Society of America conference, or provide an independent model that explains elevated temperatures in the unsaturated zone from about 12 Ma to 2 Ma; and

(B) In any analysis provided, address the effects of boundary conditions on the calculated results, and for the conductive cooling model, losses due to convection should be addressed; and

(C) Support the Marshall model by additional data (U-Th-He with error bars to overlay the theoretical cooling curve or thermochronology fission track data and analysis), including data that constrain the time of peak temperature. Support Marshall model or any other model with data from analogous systems (i.e., are there younger calderas where temperature profiles in boreholes have been measured that would support conductive heating of the unsaturated zone for kilometers away from the eruption site); or

(D) Complete the exclusion of the FEP by demonstrating that the consequences of hydrothermal activity on repository performance doesn't significantly affect the magnitude and time of the resulting expected annual dose.

(E) In addition to items A, B, and C or D, DOE should address the timing and mode of formation of secondary mineralization for the Type B faults which record elevated temperatures (calcite twinning). Explain or interpret the apparent saturated conditions of mineralization in Class B faults. If DOE would like to argue that the twinning thickness is due to frictional heating and does not reflect temperature of fluids during formation, then DOE will need to provide a technical basis for their assertion.

For TSPAI 2.02 (Comments 3, 4, 12, and J-23), NRC noted that FEP 1.2.06.00.00, hydrothermal activity as it relates to the unsaturated zone, was excluded on the basis of low consequence for basaltic magmatism and low probability for silicic magmatism. The NRC further noted that a consistent approach for the screening arguments is needed. The screening argument is considered incomplete because (1) past hydrothermal activity in the Yucca Mountain region is not clearly related to basaltic igneous activity and (2) probability screening arguments are incomplete with respect to silicic magmatism. DOE also cites unpublished studies by the U.S. Geological Survey and the University of Nevada, Las Vegas, that reportedly demonstrate hydrothermal activity was a site characteristic until about 2 million years ago. Additional unpublished work by Dublyansky and others, however, does not support this conclusion. None

of the unpublished work has supported the conclusion that the likelihood of hydrothermal activity at Yucca Mountain during the next 10,000 years is clearly less than 1 in 10,000. Absent a clear linkage to the consequences of basaltic igneous activity or a demonstrated technical basis for probability values below 1 in 10,000 in 10,000 years, DOE has an incomplete technical basis to screen FEP 1.2.06.00.00 from further consideration (NRC 2002, Table B-1).

DOE agreed to provide additional technical basis for screening FEP 1.2.06.00.00 as part of the response to ENFE 2.03, addressing the points discussed in the January 2001 ENFE Technical Exchange (NRC 2001).

NRC reported that Unsaturated and Saturated Zone under Isothermal Conditions (USFIC) 5.13 was considered complete but that additional information is needed to address TSPAI 2.02, Comments 3 and 12 (Schlueter 2003). This additional information includes a discussion of the fluid inclusion studies that support screening arguments for FEP 1.2.06.00, hydrothermal activity for the unsaturated zone. NRC staff proposed to review this information in conjunction with its review of ENFE 2.03. TSPAI 2.02, Comment 4, also addresses the screening argument for FEP 1.2.06.00, hydrothermal activity, as it relates to the saturated zone. The response to ENFE 2.03 also supplements the screening argument for this FEP.

H.1.2 Related Key Technical Issues

None.

H.2 RELEVANCE TO REPOSITORY PERFORMANCE

Past thermal and hydrothermal events in the vicinity of Yucca Mountain provide evidence of conditions that could impact flow and transport processes in the unsaturated zone. Evaluation of the thermal history of Yucca Mountain and analog evidence provided in this response for FEP 1.2.06.00.00 relates to permeability and porosity changes in fractures resulting from water-rock interaction. These hydrologic properties are important components of the UZ Flow Model contributing to TSPA. Therefore, a sufficient technical basis is required to support the exclusion of FEP 1.2.06.00.00 from TSPA-LA.

H.3 RESPONSE

The information in this report is responsive to agreements ENFE 2.03 and TSPAI 2.02 (Comments 3, 4, 12, and J-23) made between the DOE and NRC. The report contains the information that DOE considers necessary for NRC review for closure of these agreements.

H.3.1 Documentation of Timber Mountain Thermal Model of Marshall and Whelan

Marshall and Whelan (2000) first developed their model for prolonged thermal perturbation of the Yucca Mountain area by the Timber Mountain volcanic center through their analysis of the uranium–lead chronology and strontium and oxygen isotopic geochemistry of secondary calcite and opal. Strontium and oxygen isotope ratios were observed to systematically increase with time in calcite coatings in the unsaturated zone at Yucca Mountain; these changes were interpreted to reflect a gradual decrease in formation temperatures with time.

Marshall and Whelan (2001) then conducted two-dimensional thermal modeling of the Timber Mountain volcanic center to evaluate the effect of magmatism on the thermal regime at Yucca Mountain. The results of these simulations indicate that some heating would result from the presence of a large (5,000-km^3) magma chamber. During the early stages (6 to 10 Ma) of the Yucca Mountain thermal history, the simulated heating would not account for the magnitude and duration of heating indicated by the fluid inclusion measurements and oxygen isotope ratios in secondary calcite from the Yucca Mountain area (Whelan, Neymark et al. 2003). However, over the past 5 Ma, the thermal model simulations and the mineralogic temperature record are in agreement and indicate that shallow subsurface temperatures for the Yucca Mountain area are only on the order of 25°C to 40°C.

H.3.2 Effects of Boundary Conditions and Losses Due to Convection for the Conductive Cooling Model on the Calculated Results for the Marshall and Whelan Simulations

Marshall and Whelan (2001) ran thermal history simulations to evaluate the effects of the unsaturated zone, conductive versus convective heat transfer, and the impact of a more shallow magma chamber on the near-surface thermal regime. The presence of an unsaturated zone had little effect on their simulation results. However, inclusion of convective heat transfer and reduction of the depth to the top of the magma chamber both resulted in higher rates of heat transfer to the near-surface environment during the earlier stages of the thermal model simulations, resulting in higher maximum near-surface temperatures, especially in the region above the magma chamber. The increase in heat flow during the early stages of these simulation models resulted in lower temperatures beginning at about 8 Ma when compared to model simulations with conductive heat flow or deeper intrusion.

H.3.3 Comparing the Marshall and Whelan Model with Additional Thermochronology Data for Yucca Mountain and Comparison with Analogous Volcanic Centers

New geochronologic data for secondary minerals at Yucca Mountain (Neymark, Paces, et al. 2003) provide added confidence regarding the reliability of the thermochronology of Whelan, Neymark et al. (2003). Uranium-lead data for calcite and silica mineral samples indicate that inherited radiogenic lead from radon emanations, which could result in erroneously old U-Pb dates, does not appear to be a problem. Using a high-resolution (45-μm) ion microprobe, detailed uranium-series age traverses along outermost opal coatings indicate that these coatings formed gradually over a prolonged period of time. This style of formation is not consistent with a hydrothermal origin.

While the new geochronology data provide added confidence about the reliability of the Yucca Mountain secondary mineral thermochronologic record, the time-temperature trajectory does not match that predicted by the Marshall and Whelan (2001) Timber Mountain thermal history simulations during the early stages of the Yucca Mountain thermal history. These simulations are more in agreement with observations of the present-day thermal regime around the analogous Long Valley caldera. Both the Timber Mountain simulation results and the observed thermal gradients at Long Valley suggest that most shallow thermal effects from a cooling magmatic body occur directly above the magma chamber (and within the caldera margins), and that no significant shallow thermal perturbations will persist outside of the caldera over sustained (3 to

5 Ma) periods of time. Scenarios that could result in enhanced heating of the Yucca Mountain area include:

- Sustained magmatism after the cessation of volcanic activity
- Magmatic intrusion outside of the caldera margins and closer to the Yucca Mountain area
- Lateral subsurface outflow of hydrothermal fluids from the Timber Mountain area in the direction of Yucca Mountain
- Presence of additional overburden that has been subsequently eroded away above the Yucca Mountain area that would have resulted in a deeper location for the earlier part of the thermal history.

It should be noted that there is no evidence for widespread hydrothermal activity in the Yucca Mountain area associated with volcanic activity of the Timber Mountain volcanic center (Marshall, Kyser et al. 1996).

H.3.4 Mode of Formation and Timing of Calcite in Type B Faults

In their study of faults at Yucca Mountain, Gray, Stamatakos, and Ferrill (1998, 2000) and Gray, Stamatakos, Ferrill, and Evans (1999) noted the presence of secondary calcite mineralization associated with minor (Type B) faults. These faults appear to differ from the other classes of faults at Yucca Mountain in that they often contain coarse-grained secondary calcite with two-phase fluid inclusions and thick mechanical twins. By using the relation between calcite twin morphology and temperature described by Ferrill (1991, 1998) and Ferrill et al. (2004), Gray, Stamatakos, and Ferrill (2000) and Gray, Stamatakos, Ferrill, and Evans (1999) interpreted that these thick twins indicate that the calcite formed synkinematically at elevated temperature. However, Gray, Stamatakos, and Ferrill (2000) and Gray, Stamatakos, Ferrill, and Evans (1999) did not determine the calcite homogenization temperatures recorded by fluid inclusions or the absolute timing of the secondary mineralization.

Calcite from Type B faults sampled by Gray, Stamatakos, and Ferrill (2000) and Gray, Stamatakos, Ferrill, and Evans (1999) was also studied by Wilson et al. (2003). Fluid inclusions in untwinned (clear) calcite from the Exploratory Studies Facility (ESF) station 76+17.8 record homogenization temperatures of 43°C to 59°C (DTN: UN0203SPA004JC.001). These temperatures do not agree with the elevated mineralization temperatures suggested by the calcite twinning. There are two possible explanations for this discrepancy:

1. The temperatures recorded by the measured two-phase fluid inclusions may reflect actual formation temperatures for both twinned and untwinned calcite found in Type B faults. This interpretation would suggest that thick calcite twinning could develop at lower temperature (less than 100°C) conditions. Using age constraints developed by Wilson et al. (2003) for the evolution of secondary minerals at Yucca Mountain, these two-phase inclusions were likely to have formed prior to 6.29 Ma. Additional age dating and evaluation of fluid inclusion homogenization temperatures in twinned

calcite samples from Type B faults currently being conducted by the USGS could confirm this hypothesis.

2. The fluid inclusions examined in the untwinned calcite from ESF station 76+17.8 may represent a later (and cooler) stage of calcite mineralization within the Type B fault breccias. Calcite with thick mechanical twins could represent an earlier episode of calcite mineralization associated with deformation and fluid flow along the fault. The timing of this higher temperature secondary mineralization event might occur shortly after emplacement of the ash-flow tuff, when higher temperature conditions would be expected (e.g., Holt 2002).

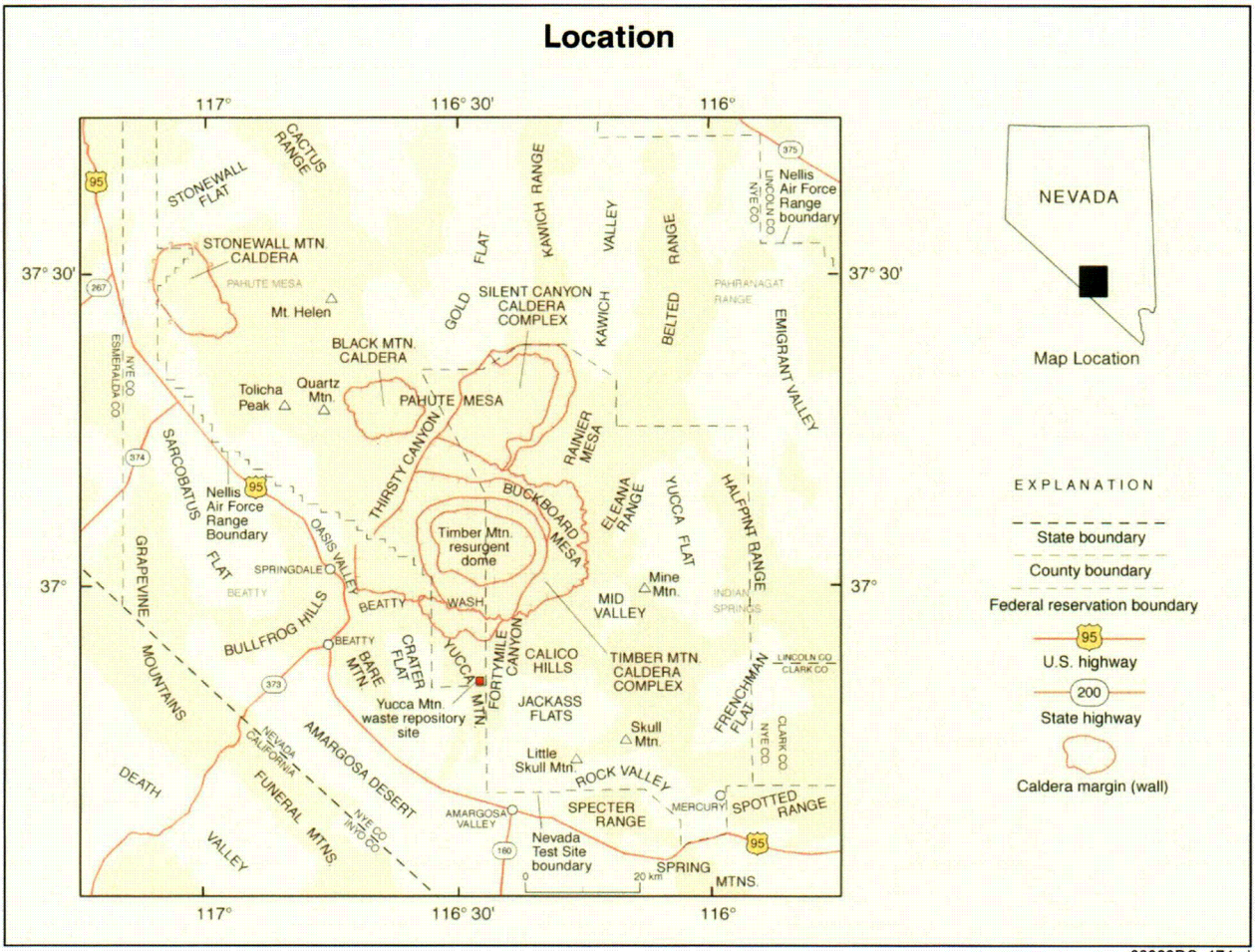
H.4 BASIS FOR THE RESPONSE

H.4.1 Documentation of Timber Mountain Thermal Model of Marshall and Whelan

Marshall and Whelan (2000) initially proposed that the variations in strontium and oxygen isotopic compositions in secondary calcite found on fracture footwalls and the bottoms of lithophysal cavities at Yucca Mountain record a gradual cooling trend. Their study predicted that temperatures were significantly above ambient thermal conditions between 6 and 12 Ma, and that these elevated temperatures were related to a regional thermal perturbation caused by the 12 Ma Timber Mountain caldera located to the north of Yucca Mountain.

The Timber Mountain-Oasis Valley caldera complex (Figure H-1), the central feature of the southwestern Nevada volcanic field, was the site of a number of voluminous ash-flow tuff eruptions, resulting in the formation of more than six calderas between >15 and 7.5 Ma (Sawyer et al. 1994). Four of the eruptive units, the Topopah Spring and Tiva Canyon members of the Paintbrush Tuff (erupted between 12.8 and 12.7 Ma) and the Rainier Mesa and Ammonia Tanks members of the Timber Mountain Tuff (erupted between 11.6 and 11.45 Ma), each have volumes greater than or equal to 900 km^3 (Sawyer et al. 1994). Hydrothermal activity and associated precious-metal mineralization (Figure H-2) was concurrent with the magmatic activity in this region (Castor and Weiss 1992). Mineralization took place between 13 and 12.5 Ma at the Wahmonie district, 13 to 11.2 Ma at the Bare Mountain district, about 11.1 to 11.4 Ma at the Mine Mountain deposit, and between 9 and 10 Ma in the Bullfrog district. The younger mineralization event in the Bullfrog district is associated with a series of rhyolitic domes, flows, and tuffs that postdate the 11.4 Ma Timber Mountain tuffs. The main secondary mineralization observed at Yucca Mountain consists of zeolitization of formerly vitric tuffs. This process has been interpreted to result from diagenetic reactions occurring shortly after emplacement of the tuffs (Broxton et al. 1987).

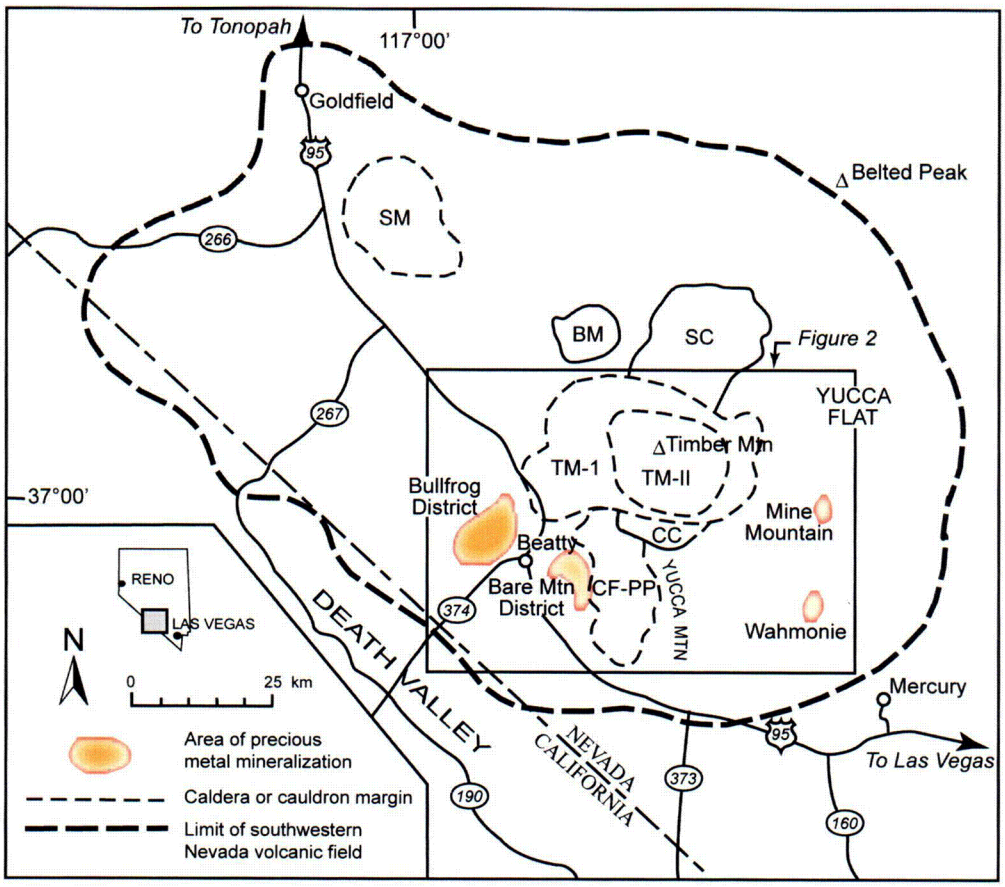
Marshall and Whelan (2001, 2004) conducted numerical simulations to determine whether the emplacement of a magma body beneath Timber Mountain could result in a prolonged thermal perturbation of the Yucca Mountain area. The numerical simulations were run using HEAT, a two-dimensional numerical simulator designed to evaluate thermal regimes around magmatic intrusions (Wohletz et al. 1999, Appendix B). The code includes the thermal contribution from the latent heat of crystallization associated with a crystallizing magma body and incorporates both conductive and convective heat flow.



Source: Slate et al. 2000; Marshall and Whelan 2004.

Figure H-1. Location Map of the Timber Mountain–Oasis Valley Caldera Complex and Surrounding Area

C01



Source: Castor and Weiss 1992, Figure 1.

NOTE: Volcanic centers include: BM = Black Mountain; CC = Claim Canyon; CF-PP = Crater Flat-Prospector Pass; SC = Silent Canyon; SM = Stonewall Mountain; TM = Timber Mountain.

Figure H-2. Southwestern Nevada Volcanic Field with Locations of Major Volcanic Centers and Areas of Precious Metal Mineralization

C02

The two-dimensional simulations used a 50-km-wide by 30-km-deep mesh with 0.5 × 0.5 km grid elements. The simulations utilized a simplified layer-cake stratigraphic model (Table H-1) that includes four rock types (volcanic, carbonate, mafic igneous, and metamorphic), along with 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). Initial conditions of the simulations were varied to evaluate the sensitivity of the model to the duration of magmatic activity, the depth of the magma chamber, the presence of an unsaturated zone, and hydrothermal circulation above the magma chamber (Table H-2). The magma chamber was assigned an initial temperature of 900°C, the surface temperature was fixed at 20°C, and the initial thermal gradient was 30°C/km.

Table H-1. Generalized Stratigraphy and Rock Properties for Marshall and Whelan Thermal Model

Rock Type	Depth Interval (km)	Density (kg/m^3)	Thermal Conductivity (W/m·K)
Volcanic rocks	0 to 5	1,800	1.3
Carbonate rocks	5 to 10	2,650	1.0
Mafic igneous rocks	10 to 20	2,850	3.0
Metamorphic rocks	20 to 30	3,300	2.0

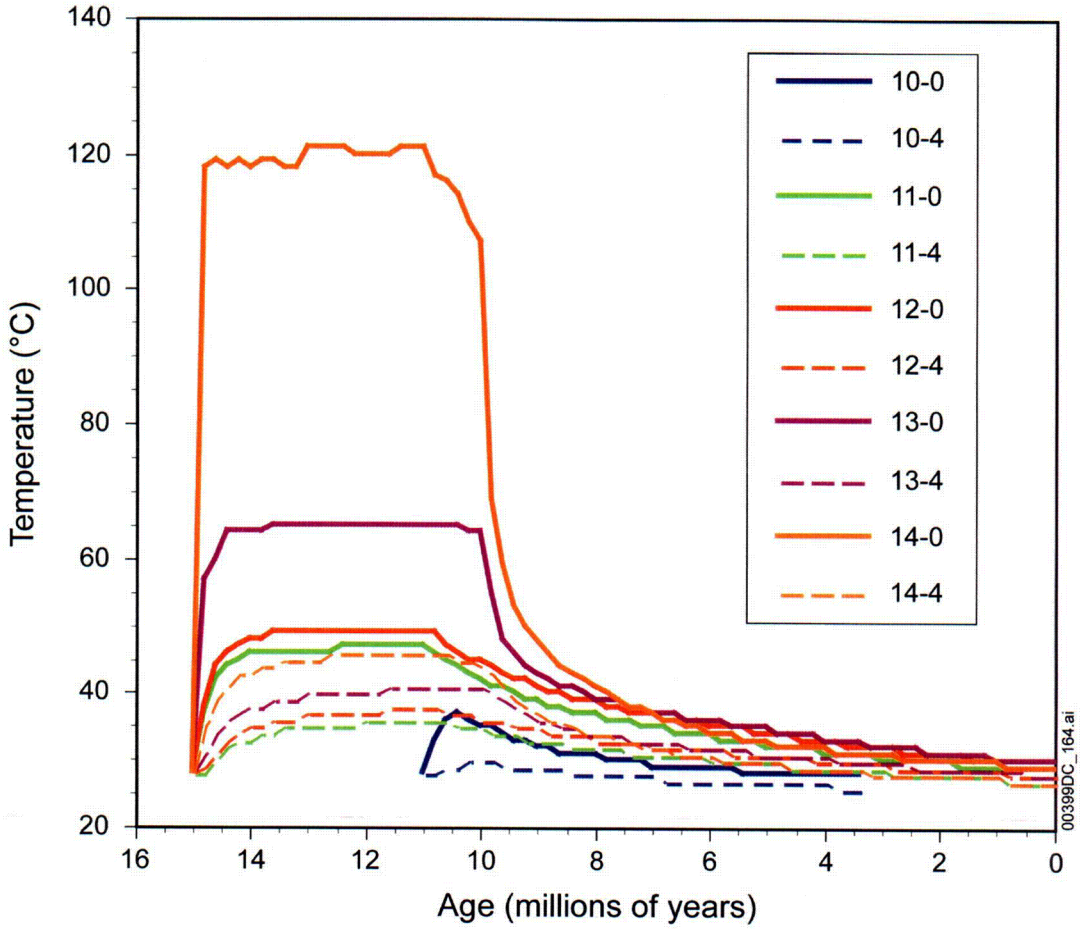
Source: Marshall and Whelan 2004.

Table H-2. Simulation Parameters for Marshall and Whelan Thermal Model

Simulation Number	Start Time (Ma)	Crustal Structure	Hydrothermal Regime	Depth to Top of Magma Chamber (km)
10	11	4-layer	None	5
11	15	4-layer	None	5
12	15	4-layer+ unsaturated zone	None	5
13	15	4-layer + unsaturated zone	0 to 2 km above magma chamber	5
14	15	4-layer + unsaturated zone	0 to 2 km above magma chamber	2.5

Source: Marshall and Whelan 2004.

The results of these simulations (Figure H-3) indicate that to produce long-lived thermal perturbations for the near-surface (0 to 500 m) environment, it is necessary to maintain a high-temperature magma chamber throughout the duration of large-scale volcanic activity at Timber Mountain (15 to 11 Ma). Adding an unsaturated interval at the surface (with lower thermal conductivity values) results in a minor delay of heat loss, while incorporating hydrothermal convection above the magma body accelerates the rate of heat transfer. 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.



Source: Marshall and Whelan 2004.

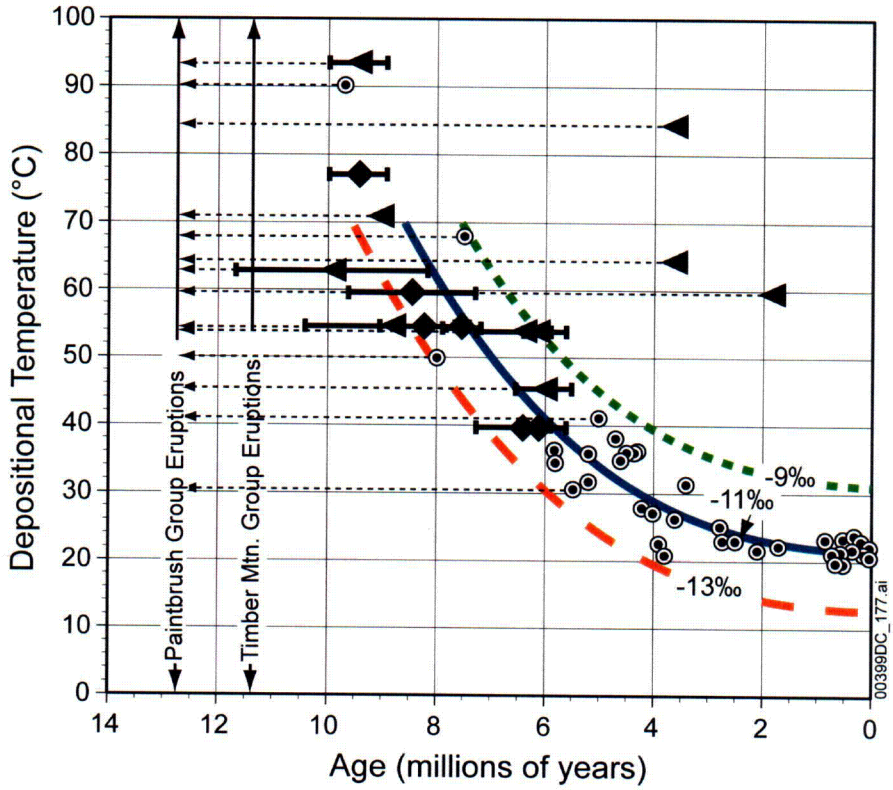
NOTE: Thermal histories presented for five different simulations (see Table H-2) at a depth of 250 m and distances of 0 and 4 km from margin of magma chamber. For the model curves, the first number is the simulation number, and the second number is the lateral distance away from the magma chamber margin.

Figure H-3. Results of Marshall and Whelan Thermal Modeling for the Timber Mountain Magmatic Center

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. The simulations portray the predicted thermal histories for locations 0 and 4 km away from the edge of the caldera (and the underlying cooling magma chamber). 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.

C03

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 (Figure H-4). Analyses of samples collected from the ESF and ECRB Cross-Drift (located approximately 6 to 10 km from the southern caldera margin) indicate temperatures that are observed to decrease with time from maximum values of around 80°C to 90°C at 9 to 10 Ma down to values of about 35°C to 55°C at 6 Ma (Whelan, Neymark et al. 2003).



Source: Whelan, Neymark et al. 2003, Figure 4.

NOTE: 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).

Figure H-4. Secondary Calcite Depositional Temperatures versus Formation Ages

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.

One way to generate a more prolonged thermal perturbation of the Yucca Mountain area would be to extend the magmatic activity of the Timber Mountain system beyond 11 Ma. While there is only minor volcanic activity associated with the Timber Mountain volcanic center after the

C04

eruption of the Ammonia Tanks member of the Timber Mountain Tuff at 11.4 Ma, it is possible that the system received continued injections of mantle-derived mafic magmas that would have provided additional heating to the region (e.g., Farmer et al. 1991). Continuing silicic volcanism at the Black Mountain caldera (9.4 Ma) and Stonewall Mountain volcanic center (7.5 Ma), both located northwest of the Timber Mountain caldera, indicates that regional silicic magmatism and associated heating persisted beyond the last voluminous eruption at the Timber Mountain caldera complex (Sawyer et al. 1994). Extending the period of magmatic heating beyond 11 Ma for the Marshall and Whelan simulations would result in higher predicted temperatures over a longer time span.

An additional source of heat to the Yucca Mountain area consists of the ash-flow sheets themselves. As an alternative but relevant model, Szymanski et al. (2000) used numerical simulations to study the early thermal history of Yucca Mountain. These simulations evaluated the conductive cooling of ash-flow tuffs after their emplacement at Yucca Mountain. From these simulations, Szymanski et al. (2000) concluded that the tuffs would cool quite rapidly, so that the tuffs would attain thermal equilibrium with the regional gradient in less than 100,000 years. This conclusion is consistent with the observations of Holt (2002) relating to the short duration of elevated temperatures associated with emplacement of ash-flow tuffs.

Szymanski et al. (2000) also evaluated the distribution of hydrothermal minerals associated with the Timber Mountain volcanic center and postulated that this event would not result in heating of the upper 250 to 300 m of the Yucca Mountain area above 35°C to 37°C. Szymanski et al. (2000) concluded that the presence of elevated fluid-inclusion temperatures in secondary minerals observed within the tuffs at Yucca Mountain resulted from hydrothermal activity that postdated the 11 to 10 Ma Timber Mountain hydrothermal event. However, the preservation of earlier isotopic signatures developed immediately after tuff emplacement (Holt 2002), the physical restriction of secondary mineralization to fracture footwalls and lithophysal cavity floors, and the limited distribution of secondary mineralization (Whelan, Paces et al. 2002) indicate that these minerals were not a product of hydrothermal alteration but instead were deposited from downward-percolating meteoric waters under unsaturated conditions.

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. Part of the discrepancy between the modeled and observed thermal histories may reflect magmatism associated with the Timber Mountain volcanic complex continuing after 11 Ma, as suggested by the presence of silicic volcanism in the region up to 7.5 Ma. Magmatism was assumed to cease at 11 Ma for the Marshall and Whelan simulations, which would lead to a shorter-lived thermal perturbation. Analysis of oxygen isotopes and trace elements in the Tiva Canyon Tuff at Yucca Mountain by Marshall, Kyser et al. (1996) indicates that the Yucca Mountain area has not been affected by large-scale meteoric water hydrothermal activity.

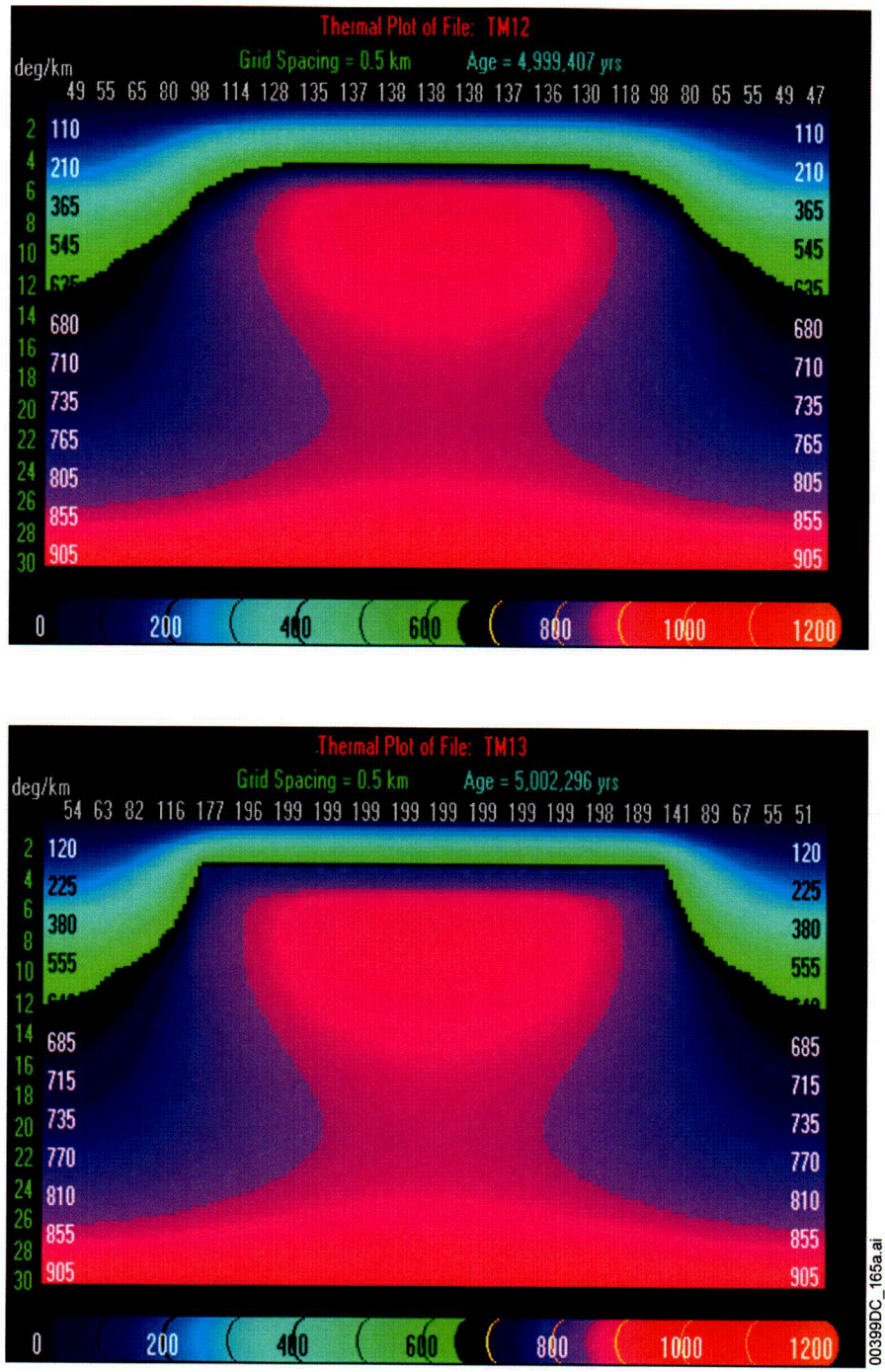
H.4.2 Effects of Boundary Conditions and Losses Due to Convection for the Conductive Cooling Model on the Calculated Results for the Marshall and Whelan Simulations

Marshall and Whelan (2001, 2004) used the two-dimensional numerical code, HEAT (Wohletz et al. 1999, Appendix B), to simulate the thermal history of the Timber Mountain volcanic center. Initial conditions, such as magma chamber size, initial magmatic temperature, regional thermal gradient, density, porosity, heat capacity, thermal conductivities, and fluid saturations, are specified for the two-dimensional gridblocks, which form an axisymmetrical representation of the magmatic system. The HEAT numerical code assigns continuous thermal gradients along the boundaries. Convective heat transfer in the magma chamber is determined by analysis of the thermal Rayleigh number. Convective heat flow in fluid saturated rock can be invoked by specifying a Nusselt number (representing the ratio of total heat transfer with convection to conductive heat transfer alone) of 100 to the region of interest. An upper boundary condition of 20°C is applied to the simulations.

A comparison of simulations 11 and 12 (Figure H-3) permits the evaluation of the effects of an unsaturated zone on the simulated thermal regime. Simulation 12 includes a 500-m-thick unsaturated zone with a lower thermal conductivity value, which should increase the time that it takes heat to diffuse to the surface. This feature results in only a minor (2°C to 3°C) increase in the temperature profile over most of the simulated thermal history.

The effects of convective heat transfer are much more pronounced for the Marshall and Whelan (2001, 2004) simulations. Simulations 12 and 13 (Figure H-3) allow for direct evaluation of the difference between conductive and convective thermal model simulations. With convective flow in a zone 0 to 2 km above the magma chamber, heat transfer to the surface occurs much more rapidly, and there is a pronounced initial increase in the thermal gradients and temperatures in the near-surface environment relative to the conductive cooling model, especially directly above the magma chamber (Figure H-5). Because convective cooling results in more rapid transfer of heat to the surface, the predicted temperatures for the convective model simulations become lower than those for the conductive model simulations after about 3 Ma after the cessation of magmatism.

Another initial condition evaluated by Marshall and Whelan (2001, 2004) in their simulations was the effect of the depth of emplacement of the magma body. Simulations 13 and 14 compare the effect of shifting the depth of the top of the magma chamber from 5 to 2.5 km below the surface. The thermal history for shallower magma chamber (simulation 14) has higher near-surface temperatures (about 120°C versus about 65°C for the location next to the magma chamber margin, and about 45°C versus about 40°C for the location 4 km away from the margin) during the initial phases of the simulation that result from the significantly higher thermal gradients that result from having a 900°C magma chamber located only 2.5 km from the surface. Over time, the shallower magma chamber cools more rapidly, so that by 7 Ma, temperatures are higher for the simulation with the deeper magma chamber (Figure H-3). Similar responses relating to the impact of a lower thermal conductivity layer, the effects of conductive versus convective heat transport, and the effect of the depth of magma chamber emplacement to thermal modeling were observed by Stimac et al. (1997).



Source: Marshall and Whelan 2004.

NOTE: Top graphic is for simulation 12 (conduction only); bottom graphic is for simulation 13 (conduction plus convection). Cross section is 50 km wide by 30 km deep (depth scale is the far left scale in each of the models). Frames represent thermal profiles at 10 Ma. Thermal gradients (°C/km) are listed along the top margin of the models at 2.5-km intervals; simulated temperatures (°C) are presented along the sides of the models at 2.5-km intervals. Surface temperatures are fixed at 20°C. A color temperature scale (°C) is presented along the bottom margin of the models. See Table H-2 for details of simulations.

Figure H-5. Thermal Profile for Simulations 12 and 13 of Timber Mountain Caldera Complex

C05

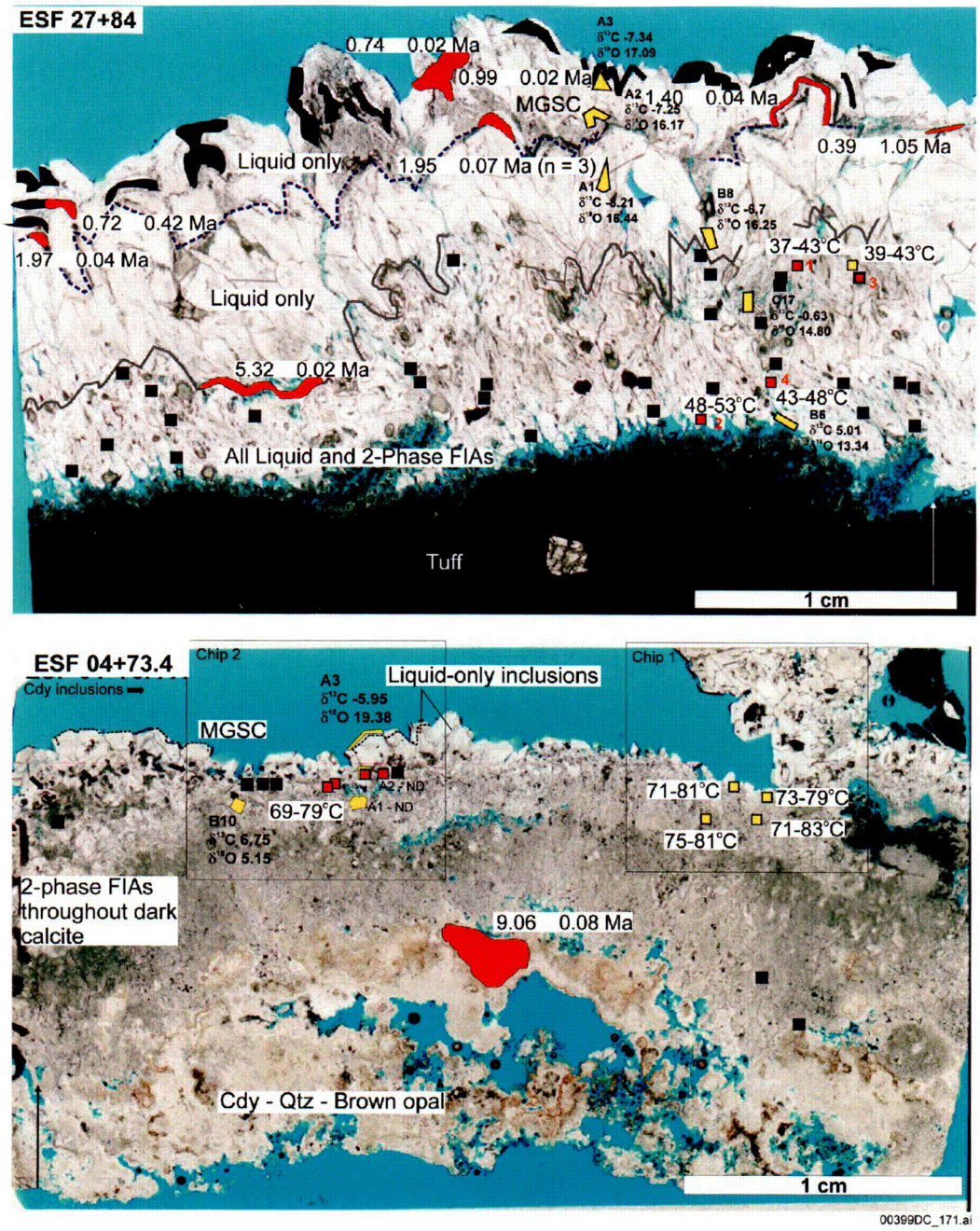
H.4.3 Supporting the Marshall and Whelan Model with Additional Thermal-Chronology Data for Yucca Mountain and Comparison with Analogous Volcanic Centers

H.4.3.1 Thermochronology

Age constraints for the Yucca Mountain thermochronology (Figure H-4) are based on the microstratigraphy of secondary minerals and the radiometric ages of host ash-flow tuffs and interlayered chalcedony and opal deposits. In all cases, the maximum ages for the secondary calcity mineralization are constrained by the $^{40}Ar/^{39}Ar$ ages of the host tuffs (e.g., 12.8 ±0.3 Ma in the case of the Topopah Spring Tuff (Sawyer et al. 1994, Table 3)). The uranium–lead and uranium-series dating of opal and chalcedony provide better temporal constraints for when the fluid inclusions in calcite were formed. These minerals, along with calcite, form layers that coat some of the open fractures and lithophysal cavities at Yucca Mountain (Paces et al. 2001). The microstratigraphy of these interlayered minerals, together with radiometric age determinations of opal and chalcedony and temperature estimates derived from fluid inclusion homogenization measurements and oxygen isotope compositions of calcite, constrain the time-temperature record for Yucca Mountain (Figure H-6).

Results of the uranium-thorium-helium radiometric age-dating work related to Yucca Mountain thermochronology, including 2σ error estimates, are reported by Neymark, Amelin, and Paces (2000, Table 4), by Neymark, Amelin, Paces, and Peterman (2002, Tables 2 and 3), and by Wilson et al. (2003, Tables 3 and 4). Details involving the calculation of U-Pb ages are provided by Neymark, Amelin, and Paces (2000, Appendix 1). Examples of calculated 2σ error values are illustrated for specific Yucca Mountain samples in Figures H-7 and H-8. Issues associated with the reliability of radiometric age measurements of secondary silica deposits at Yucca Mountain are discussed below.

Pashenko and Dublyansky (2002) questioned the reliability of uranium–lead dating of the secondary opal deposits at Yucca Mountain. They noted that radiogenic lead generated from the decay of radon present in the fractures and cavities may be incorporated into the opal, which could lead to erroneously old uranium–lead ages. This issue was addressed by Neymark, Paces et al. (2003), who used new uranium–lead results from secondary calcite and silica collected from Yucca Mountain to confirm that age determinations made using the uranium–lead dating technique are reliable. Uranium–lead analyses of calcite, which has very low initial uranium concentrations, indicate that calcite does not have appreciable amounts of excess ^{207}Pb (Figure H-9), which would be expected if significant amounts of inherited lead were generated by radon emanation and incorporated into precipitating secondary minerals. Uranium–lead isochron diagrams (Figure H-7) constructed for coeval chalcedony samples obtained from a single microstratigraphic layer yield concordant ages and show no indication of initial excesses of ^{206}Pb or ^{207}Pb.

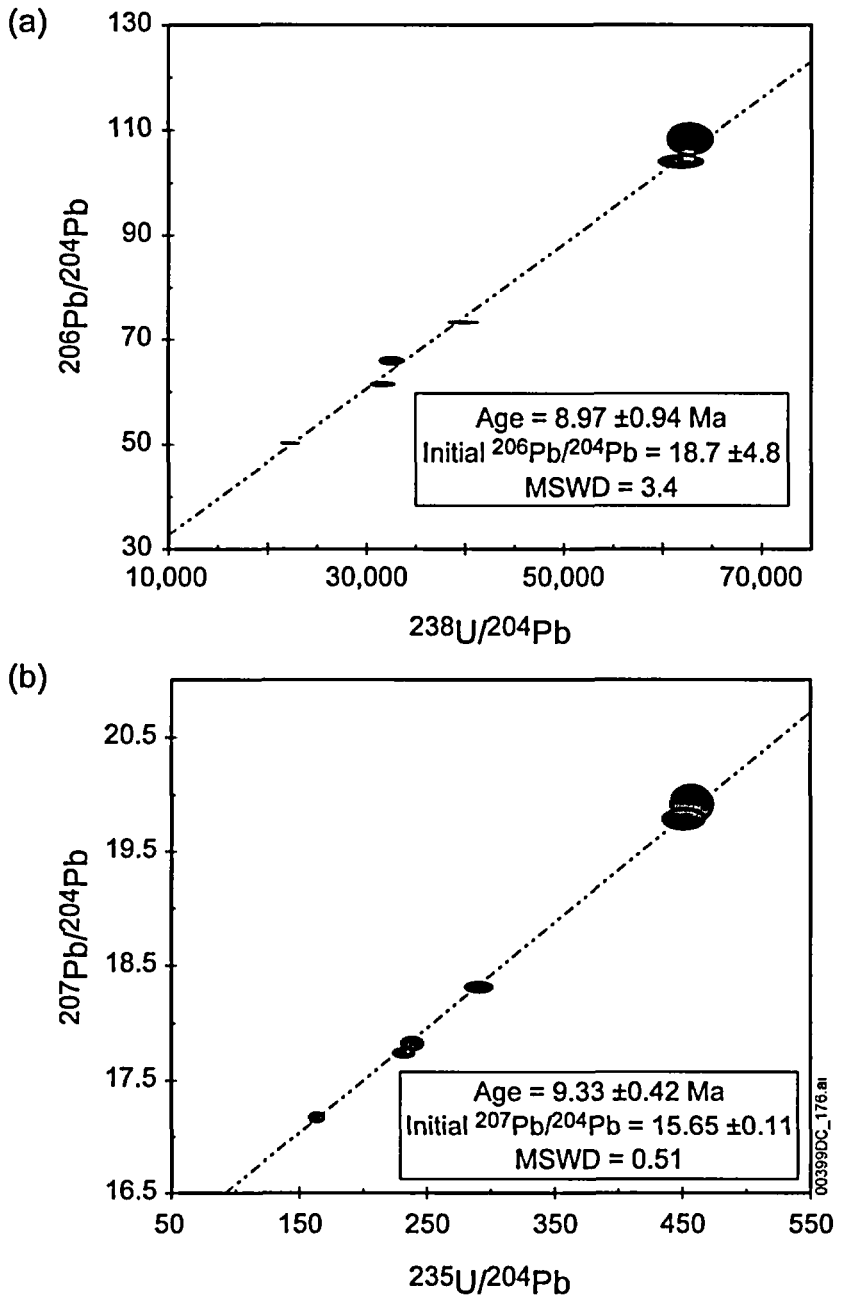


Source: DTN: UN0203SPA004JC.001.

NOTE: Upper sample (constraining the youngest age for two-phase inclusions) is from a lithophysal cavity at ESF station 27+84; lower sample (constraining the maximum age for two-phase inclusions) is from a fracture at ESF station 04+73.4. Arrows denote microstratigraphic direction toward younger ages. Solid gray line is the boundary between liquid-only fluid inclusion assemblage zone and two-phase and all-liquid fluid inclusion assemblage zone. Blue dashed line is the boundary between magnesium-growth zoned sparry calcite and underlying secondary minerals. Black squares are the location of primary two-phase fluid inclusion assemblages. Yellow and red squares are the location of two-phase fluid inclusion assemblages that were examined using microthermometry. Yellow polygons are the location of carbon and oxygen stable isotopic analyses. Black irregular shapes are opal and chalcedony. Red irregular shapes are dated opal. MGSC = magnesium-growth zoned sparry calcite; FIA = fluid inclusion assemblage; Cdy = chalcedony; Qtz = quartz.

Figure H-6. Doubly Polished Thin Sections Constraining the Ages of Calcite with Two-Phase Fluid Inclusions

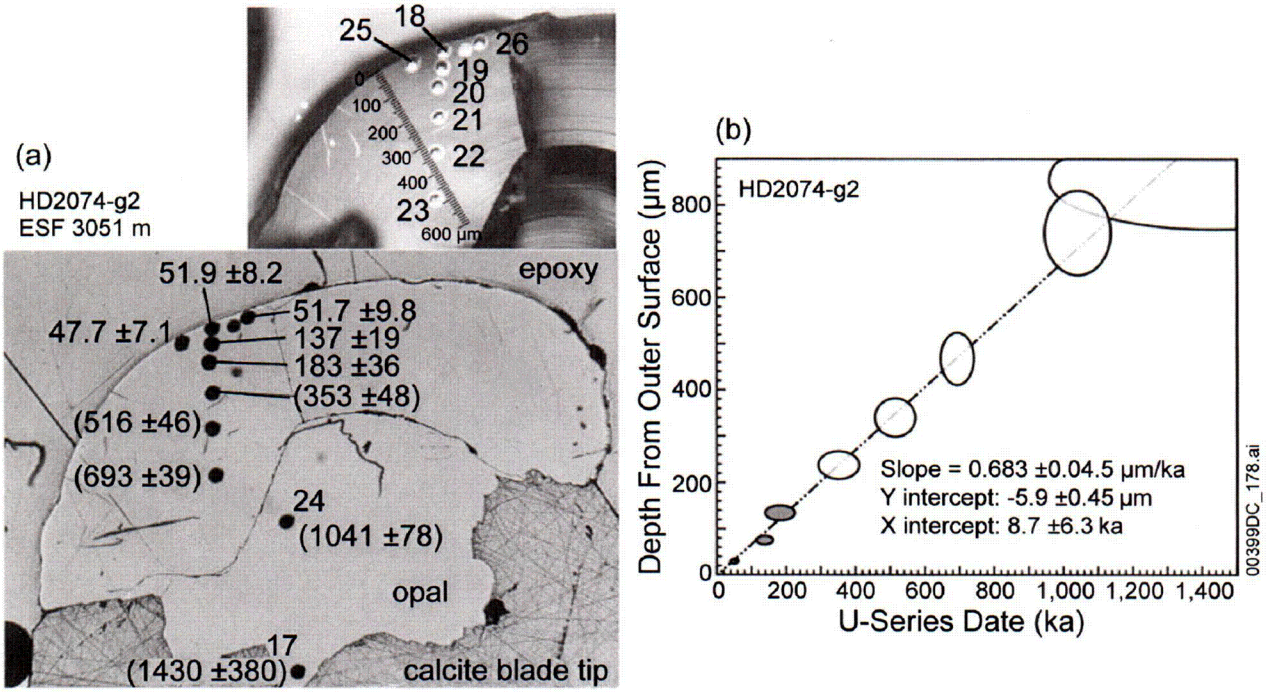
C06



Source: Neymark, Paces et al. 2003, Figure 10.

NOTE: Y-intercept values correspond to the initial lead inherited from the unsaturated zone water. Data point ellipses represent 2σ error values. MSWD is the mean square weighted deviation.

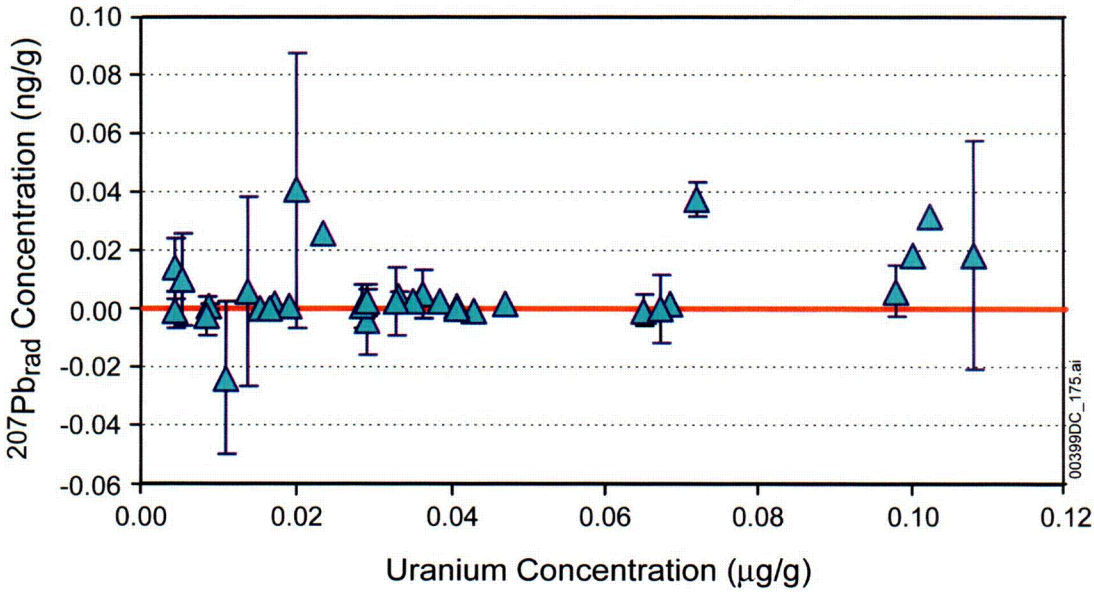
Figure H-7. $^{206}Pb/^{204}Pb$ versus $^{238}U/^{204}Pb$ and $^{207}Pb/^{204}Pb$ versus $^{235}U/^{204}Pb$ Isochron Plots for Coeval Chalcedony Samples from a Single Microstratigraphic Layer in Coating HD2021 from Exploratory Studies Facility Station 12+21.83



Source: BSC 2004a, Figures 6.14.3-1 and 6.14.3-3.

NOTE: ^{230}Th/U ages are given in thousands of years, and ^{234}U/^{238}U model ages (calculated using an initial activity ratio of 7.38 ±0.19) are given in parentheses in thousands of years. Ellipses represent 2σ errors for ^{230}Th/U ages (shaded) and ^{234}U/^{238}U model ages (open). Errors in microstratigraphic depth are assumed to be 10% of the measured value.

Figure H-8. Cross Section of Opal Coating and Associated Uranium-Series Model Ages versus Distance from Outer Surface for Sample HD2074-g2 from Exploratory Studies Facility Station 30+51



Source: Neymark, Paces et al. 2003, Figure 7.

Figure H-9. Relation between Uranium Concentration and Common Lead-Corrected ^{207}Pb$_{rad}$ in Secondary Calcite Samples from Yucca Mountain

C07

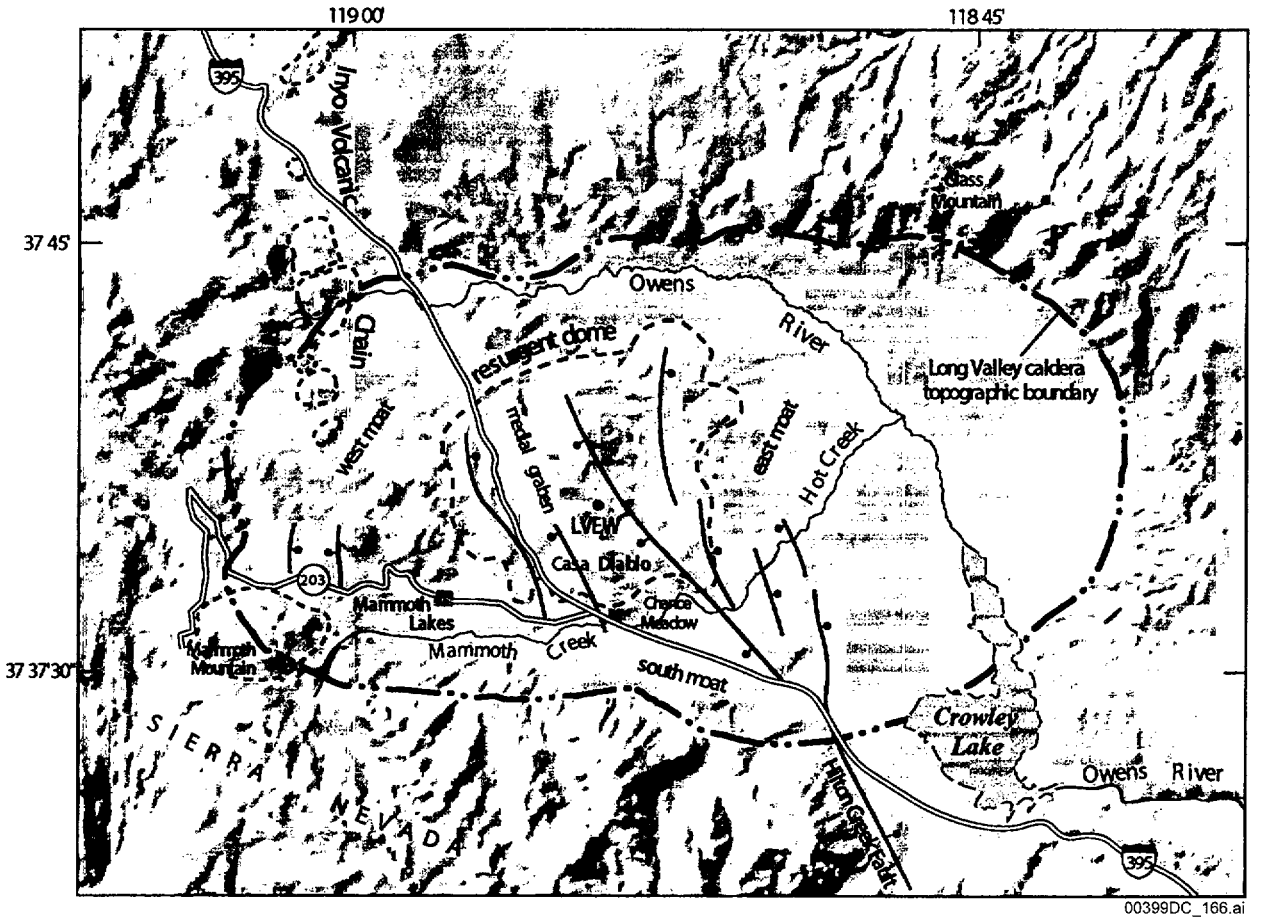
In addition, Neymark, Paces et al. (2003) utilize new ion-microprobe uranium-series age dates that provide higher spatial resolution (about 45 μm) to establish that the outermost opal coatings formed slowly (less than 1 mm per million years) over long (greater than or equal to 1 million years) periods of time (Figure H-8). Such a growth pattern would not be consistent with secondary mineralization that resulted from a short-lived pulse of hydrothermal activity.

These geochronology studies provide added confidence in the reliability of the Yucca Mountain thermochronology as established by the record of secondary calcite and silica. However, the record of very gradual cooling from temperatures of around 85°C at 9 to 10 Ma to values of about 40°C at 6 Ma (Figure H-4) is not consistent with the simulation results of Marshall and Whelan (2004) (Figure H-3), which predict lower temperatures with more rapid cooling for the Yucca Mountain area. 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. Continued regional silicic volcanism (Sawyer et al. 1994) at the Black Mountain caldera (9.4 Ma) and Stonewall Mountain volcanic center (7.5 Ma) indicate that intrusion and magmatic heating of the Yucca Mountain area after 11 Ma may have occurred.

H.4.3.2 Natural Analogs

To determine whether cooling magmatic intrusions can provide a long-term (4 to 5 Ma) heat source for areas outside of the caldera margin, the Timber Mountain caldera-heating model proposed by Marshall and Whelan (2000, 2001) can be compared with observed thermal gradients around similar but younger volcanic centers. In this section, one silicic volcanic center, the Long Valley Caldera, is evaluated to determine whether there is evidence for elevated temperatures comparable to those recorded by the secondary minerals at Yucca Mountain outside of the caldera margins for these systems. The Long Valley Caldera was selected as an analog for the early thermal history of the posteruptive Timber Mountain volcanic center because the volcanic history of the Long Valley volcanic center is well constrained, and there are abundant present-day heat flow data available for the Long Valley Caldera and its surroundings.

The Long Valley Caldera is located in east–central California (Figure H-10) and was formed by the eruption of the about 600 km^3 Bishop Tuff at around 730,000 years ago (Sorey, Suemnicht et al. 1991). There has been volcanic activity in this area over the past 3 Ma, with the most recent eruptions resulting in the emplacement of the Inyo domes less than 800 years ago (Bailey et al. 1976). The presence of active thermal springs (Sorey and Lewis 1976; Sorey 1985) and elevated subsurface temperatures (Blackwell 1985; Sorey, Suemnicht et al. 1991; Farrar et al. 2003) within the caldera indicate the presence of elevated heat flow resulting from intrusion of magma and hydrothermal circulation. Dating of hot springs deposits indicates that there have been distinct thermal pulses subsequent to the caldera-forming eruption, and these have been interpreted to be related to more recent episodes of volcanic activity (Sorey, Suemnicht et al. 1991).



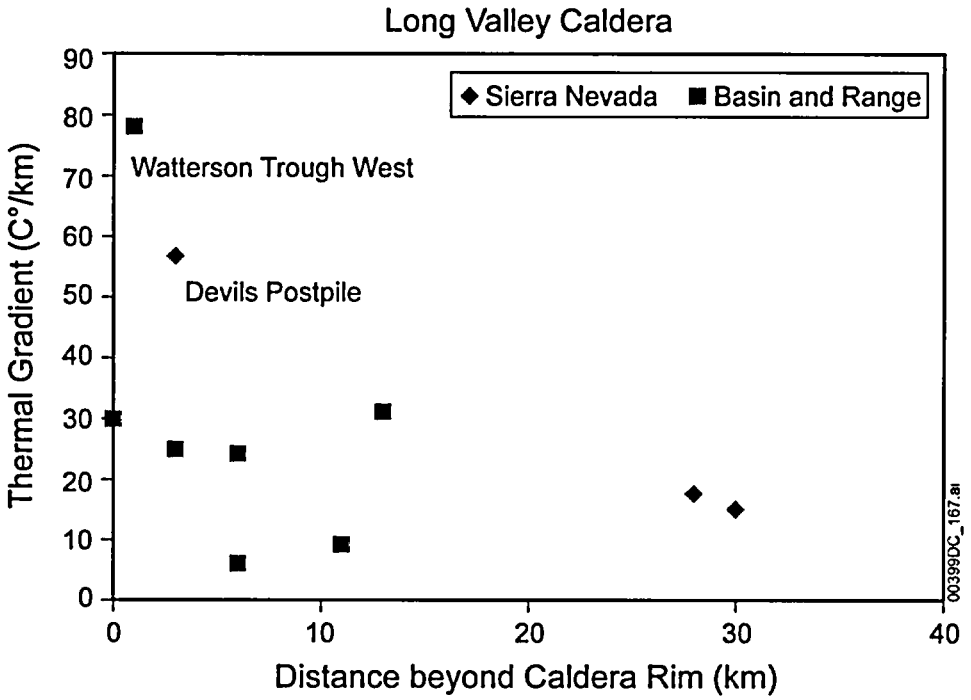
Source: Farrar et al. 2003, Figure 1.

Figure H-10. Shaded Relief Map of the Long Valley Caldera Area

While elevated subsurface temperatures have been encountered within the Long Valley caldera, there is little evidence for significant heating outside of the caldera margin. Lachenbruch et al. (1976) used temperature measurements from a series of wells drilled to depths of 150 to 300 m located 0 to 30 km outside of the caldera margin to determine whether there were any noticeable thermal effects caused by the volcanic center on the surrounding region (Figure H-11).

The Long Valley caldera is located on the boundary of two distinct thermal regimes, the Sierra Nevada (with lower heat flow) and the Basin and Range Province (with higher heat flow). While there are elevated thermal gradients for two examined locations immediately adjacent to the caldera margin, recorded heat flow values were within the normal range of values for each thermal province (Lachenbruch et al. 1976). Areas with higher heat flow (Watterson Trough West and Devils Postpile) are located within 3 km of the caldera margin; these locally elevated values may reflect shallow geothermal outflow to the east (Watterson Trough West site) or fairly recent intrusion of magma near the western margin of the caldera (Devils Postpile location). However, the general observation made by Lachenbruch et al. (1976), supported by simple heat conduction models, is that 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 (as indicated in Figure H-11). Localized heating can be expected for areas where subsurface outflow of hydrothermal fluids occurs, such as may be the case for the Watterson Trough West locality.



Source: Lachenbruch et al. 1976, Table 1.

Figure H-11. Plot of Measured Thermal Gradient versus Distance Outside the Caldera Margin for Wells around the Long Valley Caldera

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 decline quickly away from the caldera margin. Enhanced heat transfer to regions outside the caldera would result primarily from lateral outflow of hydrothermal fluids, presumably along structural features with enhanced permeability, as is observed at the Valles caldera geothermal system (Goff et al. 1988), another young, well-studied silicic volcanic center that is analogous to Timber Mountain.

H.4.4 Mode of Formation and Timing of Calcite in Type B Faults

A series of published abstracts by Gray, Stamatakos, and Ferrill (1998, 2000) and Gray, Stamatakos, Ferrill, and Evans (1999) reported the presence of secondary calcite associated with minor (Type B) faults at Yucca Mountain. These faults contain narrow (2 to 20 cm thick) breccia zones with clasts of wall rock tuff set in a matrix of abundant, coarse-grained secondary calcite, together with chalcedony and (or) opal. Some of the calcite contains two-phase fluid inclusions and thick mechanical twins. Lesser amounts of postkinematic (untwinned) calcite were also observed. Gray, Stamatakos, and Ferrill (1998, 2000) and Gray, Stamatakos, Ferrill,

and Evans (1999) use the presence of the thick calcite twins to infer elevated deformation temperatures. While these studies do not report actual temperature estimates, work by Ferrill (1991, 1998) and Ferrill et al. (2004, Figure 2) indicates that thick calcite twins are indicative of temperatures on the order of 170°C to 200°C.

Gray, Stamatakos, and Ferrill (2000) indicate that the twinned calcite samples record a higher temperature episode of alteration than is indicated by the calcite mineralization found in lithophysal cavities and fracture footwalls, where fluid inclusion homogenization measurements indicate depositional temperatures that decrease with time from values from about 83°C down to ambient values (e.g., Wilson et al. 2003). Gray, Stamatakos, and Ferrill (2000) did not analyze the fluid inclusions observed in the twinned calcite samples, which would have provided a more precise estimate of the calcite formation temperatures.

Wilson et al. (2003) analyzed fluid inclusions from calcite collected from one Type B fault located at station 76+17.8 (Figure H-12) that had been previously sampled by Gray and others. These fluid inclusions were located in clear, untwinned calcite crystals that form part of the matrix of the fault breccia (Figure H-13). The calcite observed in the breccia is interpreted to have formed in two different stages; an early stage with dark, dirty calcite forming along the sides of the fault and a later stage with clear calcite within the interior of the breccia zone. Fluid inclusion homogenization temperatures (T_h values) obtained from clear calcite from this location (DTN: UN0203SPA004JC.001) range from 43°C to 59°C (Figure H-14). Fluid inclusion results were not reported for the earlier dirty calcite.

While Wilson et al. (2003) did not conduct radiometric dating for samples from the ESF station 76+17.8 location, the age relations that they determined for two-phase fluid inclusions for samples within the ESF and ECRB indicate that the inclusions formed between 5.32 ±0.02 and 9.06 ±0.08 Ma (Figure H-6). Most higher-temperature (greater than 45°C) two-phase fluid inclusions are older than 6.29 ±0.3 Ma, which further constrains the probable age of the clear calcite in the ESF station 76+17.8 fault breccia.

Microstratigraphic relations within the ESF station 76+17.8 fault breccia indicate that the dark calcite (potentially equivalent to the twinned calcite of Gray, Stamatakos, and Ferrill (2000) and Gray, Stamatakos, Ferrill, and Evans (1999)) predates the studied clear calcite grains (DTN: UN0203SPA004JC.001). The time–temperature relation for precipitation of secondary calcite at Yucca Mountain indicates that temperatures have progressively decreased with time (e.g., Whelan, Neymark et al. 2003; Wilson et al. 2003); thus, it is possible that the earlier calcite in the ESF station 76+17.8 fault breccia was deposited at temperatures greater than those recorded by the fluid inclusions in the adjoining clear calcite. Wilson et al. (2003), Dublyansky et al. (2001), and Whelan, Neymark et al. (2003) measured maximum fluid inclusion homogenization temperatures of 83°C, 85°C, and 89°C, respectively, for two-phase inclusions in secondary calcite samples from Yucca Mountain. These temperatures are still much lower than those indicated by the presence of thick mechanical twins.

This apparent discrepancy can be resolved through analysis of fluid inclusions trapped in the older twinned calcite crystals. The U.S. Geological Survey is in the process of examining and characterizing samples of calcite collected from Type B fault breccias (BSC 2004b,

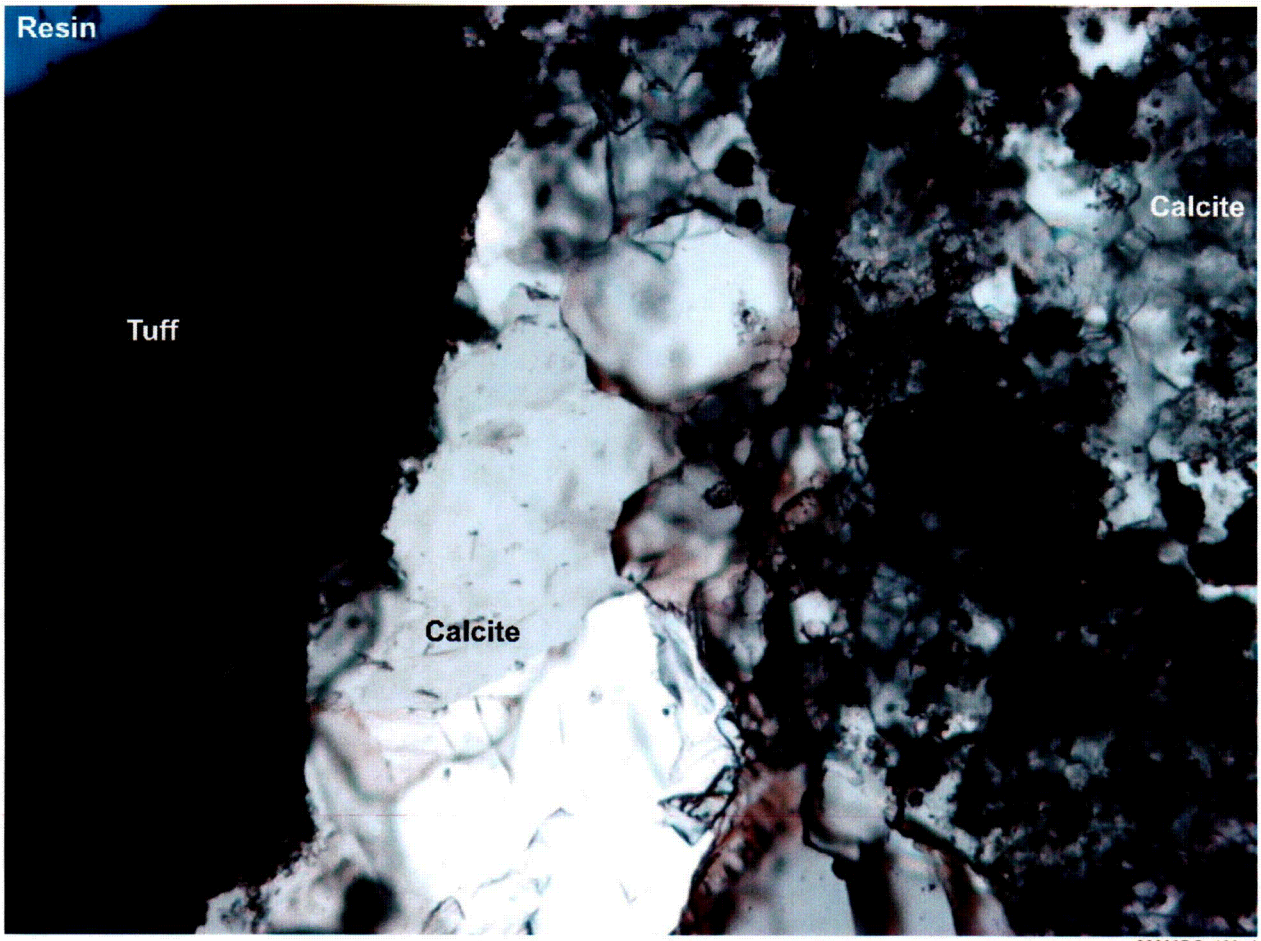
Section 1.2.6) to test the hypothesis of rapid deposition at elevated temperatures and to constrain the timing of calcite formation in these breccias.

00399DC_168.ai

Source: DTN: UN0203SPA004JC.001.

Figure H-12. Type B Fault in Exploratory Studies Facility Station 76+17.8 with Calcite-Cemented Breccia

C08



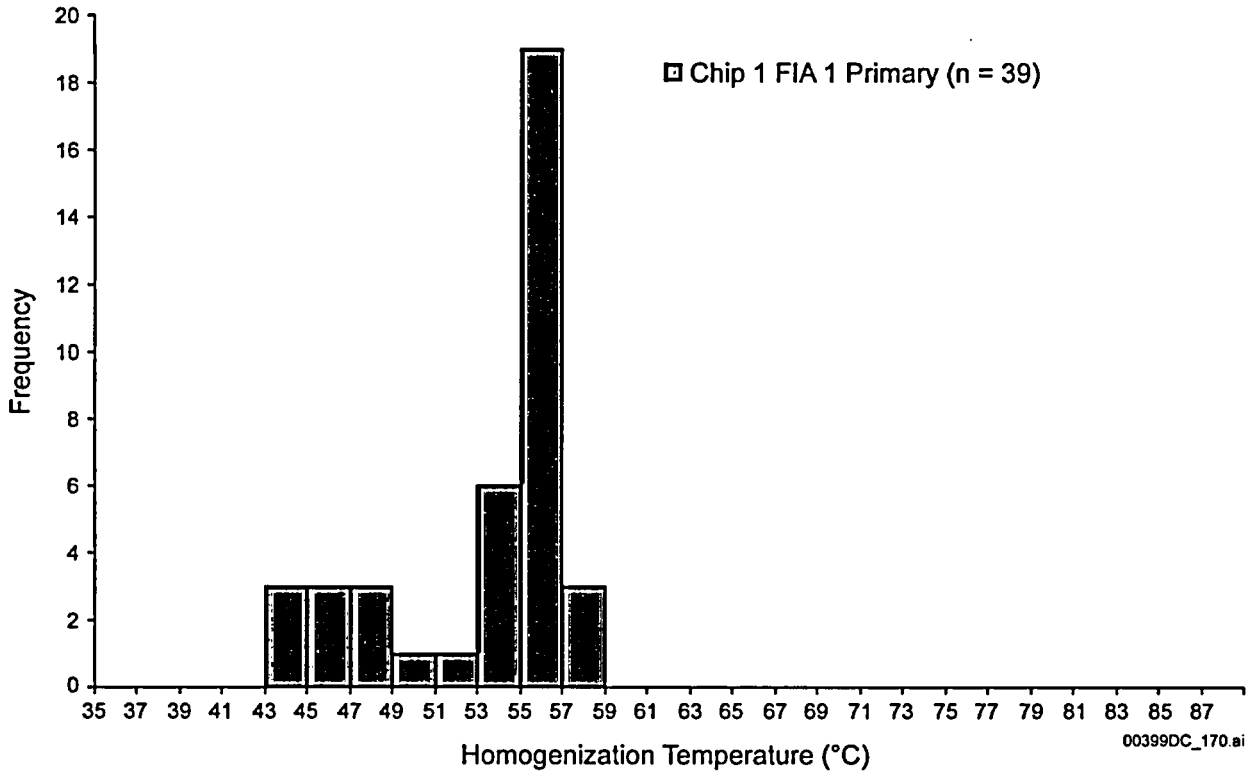
00399DC_169.ai

Source: DTN: UN0203SPA004JC.001.

NOTE: Darker calcite (perhaps with minor associated quartz and fluorite) is interpreted to have formed first, followed by later clear calcite. Fluid inclusion measurements were made on the clear calcite grains. Image width is approximately 3.5 mm.

Figure H-13. Photomicrograph of Fault Breccia at Exploratory Studies Facility Station 76+17.8

C09



Source: DTN: UN0203SPA004JC.001.

Figure H-14. Histogram of Fluid Inclusion Homogenization Temperatures for Calcite Sample from Exploratory Studies Facility Station 76+17.8

The existing information indicates that the earliest calcite found in the fault breccias was deposited during deformation and movement along these minor faults, which occurred during an early stage in the history of Yucca Mountain (prior to 6.29 Ma); however, the exact age and temperature conditions of this event have not yet been established. While the range of T_h values (43 C to 59°C) for fluid inclusions from clear calcite in the fault breccia from ESF station 76+17.8 (DTN: UN0203SPA004JC.001) and the maximum fluid inclusion homogenization temperature (83°C) obtained by Wilson et al. (2003) from hundreds of secondary calcite samples indicate that the high (greater than 170°C) temperatures inferred from the presence of mechanical twins is not correct, there still remains the possibility that (1) the early synkinematic calcite in the fault breccias represents a mineralization episode that may not have been captured by the Wilson et al. study and (2) the twinned calcite was formed during a very early, higher temperature event. Such temperatures would most likely have occurred shortly after emplacement of the ash-flow tuff deposits at Yucca Mountain, when degassing and cooling of the ash-flow tuff can result in devitrification, vapor-phase alteration, and development of localized meteoric-hydrothermal activity in the upper parts of ash-flow sheets (Holt 2002). Gray, Stamatakos, and Ferrill (2000) note that the calcite mineralization observed in the Type B faults is not encountered in the intrablock and block-bounding faults, which would be likely candidates for fluid flow and mineralization in the event of widespread hydrothermal alteration. The absence of pervasive hydrothermal mineralization of the Yucca Mountain tuffs is consistent with the interpretation that large-scale hydrothermal activity has not occurred in the Yucca Mountain area.

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H.5.2 Data, Listed by Data Tracking Number

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