Simulating the Prolonged Cooling History of the Shallow Volcanic Section at Yucca Mountain, Nevada

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INTRODUCTION

Yucca Mountain is a ridge of mostly welded tuff originating from a series of nested calderas known as the Timber Mountain caldera complex (Byers et al., 1976). Three of the eruptions that produced these extensive ash-flow sheets are the result of some of the largest explosive eruptions known with estimated eruption volumes in excess of 1000 km^3 (Mason et al., 2004). As part of site-characterization activities conducted for the proposed (now withdrawn) licensing of a radioactive waste repository, tunnels (Fig. 1) were constructed which provided access to two of these ash-flow sheets, the Tiva Canyon Tuff (12.7 Ma) and the Topopah Spring Tuff (12.8 Ma) as well as nonwelded volcanic tuffs in between these major ash flows. A third major unit, Rainier Mesa Tuff (11.6 Ma), is not currently exposed on the crest of Yucca Mountain, but 100 m of this unit may originally have been present (Fig. 2; ages from Sawyer et al., 1994).

Within the welded Topopah Spring Tuff and the Tiva Canyon Tuff, calcite and opal occur as sparse coatings on fracture surfaces and within lithophysal cavities. These secondary minerals precipitated from downward-percolating water over most of the post-depositional history of the rock mass (Paces et al., 2001). Fluid inclusions within calcite as well as $\delta^{18}O$ values indicate that some of the secondary mineral precipitation occurred at temperatures greater than modern-day temperatures. Geochronologic studies, primarily U-Pb measurements on associated opal, constrain the higher temperatures to the older portions of the coatings. Various lines of evidence suggest a prolonged cooling history. The gradually decreasing temperatures in the Yucca Mountain unsaturated zone (UZ), together with the proximity to a large caldera complex, suggest that the cooling of a subcaldera batholith could explain the thermal history. This hypothesis was supported by a simple one-dimensional analytical heat flow model (Marshall and Whelan, 2000). This hypothesis has been disputed, however, by other researchers who state "in the geological history of Yucca Mountain, there are no known thermal events, like intrusions of large-volume magmatic bodies, that could have led to the increase in temperatures in the unsaturated zone" (Dublyansky et al., 2001). It should be noted that there is only scant evidence for hydrothermal alteration of the UZ tuffs at Yucca Mountain at the time of volcanism (Holt, 2002). Younger portions of the secondary minerals faithfully record climate-related signals that clearly indicate an origin from meteoric water (Paces et al., 2010).

This poster summarizes numerical modeling studies that simulate the thermal history within the known geologic framework of the Timber Mountain caldera complex. The results of these simulations were published in Whelan et al. (2008) and in Bryan et al. (2009).

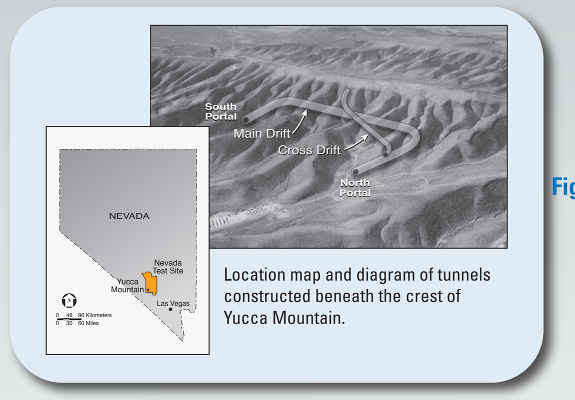


Figure 1

Location map and diagram of tunnels constructed beneath the crest of Yucca Mountain.

Figure 2

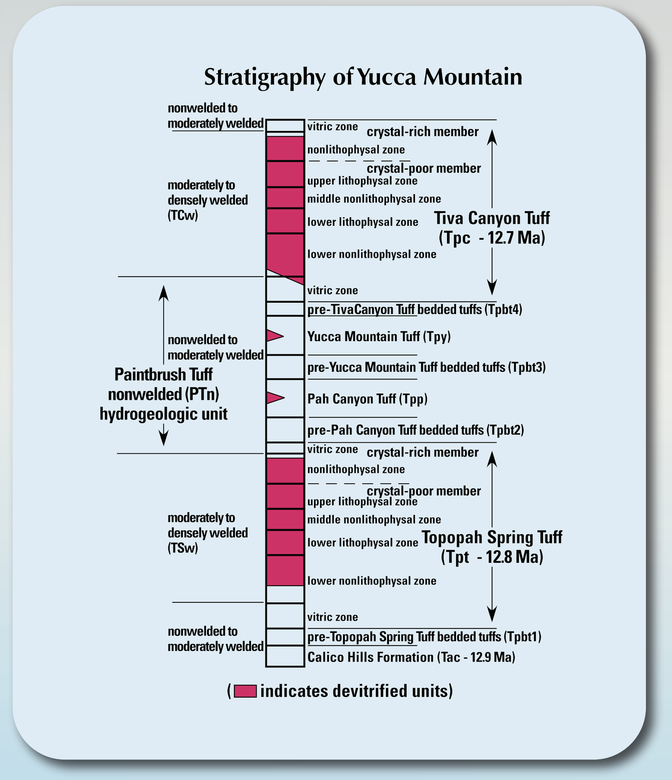
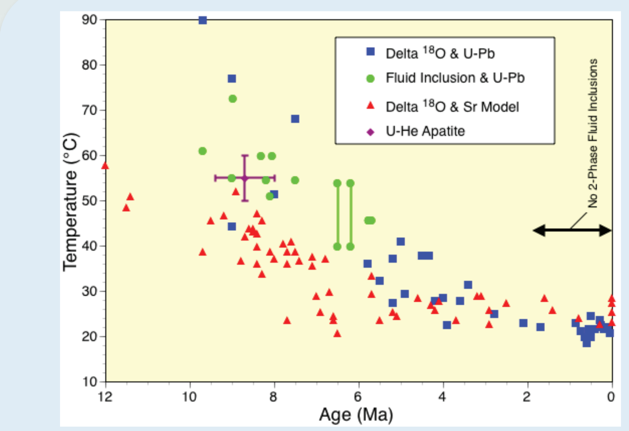


Figure 3



Formation temperatures of calcite from Yucca Mountain as a function of age. Temperatures are estimated from oxygen isotope values and fluid inclusion homogenization. Ages determined by U-Pb dating of associated opal and chalcedony and by a strontium-isotope evolution model (Marshall and Futa, 2001). One U-Th-He apatite cooling age has also been determined from the Topopah Spring Tuff.

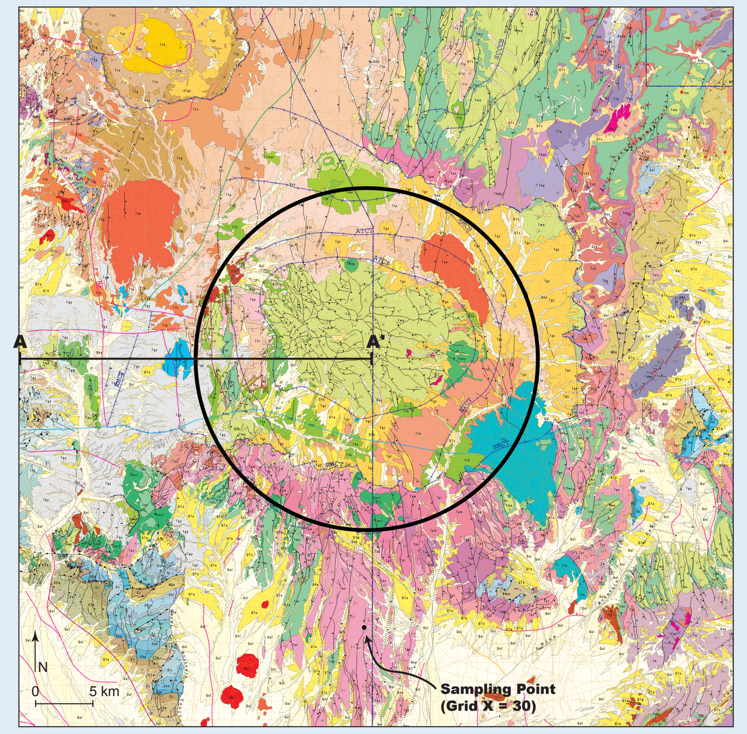
THERMAL HISTORY OF YUCCA MOUNTAIN

Secondary calcite and opal are present as fracture footwall coatings and as cavity floor coatings; these minerals formed from downward-percolating water over most of the time between at least 10 Ma and the present (as young as 8 ka). Both fluid inclusion homogenization temperatures and temperatures derived from oxygen isotope measurements indicate that some calcite formed at temperatures greater than the present-day ambient temperatures within the unsaturated zone at Yucca Mountain. Age constraints, primarily from U-Pb dating of opal, chalcedony, and quartz, further indicate that the higher temperature portions of the coatings are restricted to the oldest parts of the coatings, the material closest to the tuff substrate. A prolonged cooling of the unsaturated zone is suggested by these data as well as by a single U-Th-He age on apatite from a pumice clast (Fig. 3).

Because the data indicate a monotonic decrease in temperaure with time, it is likely that the unsaturated zone at Yucca Mountain was responding to a nearby thermal perturbation for millions of years after eruption of the Paintbrush Group units. The most probable source of a large thermal perturbation is the emplacement of magma into the shallow crust beneath Timber Mountain. The modeling efforts have been directed solely at the cooling of a large subvolcanic batholith in the vicinity of Timber Mountain. Figure 4 shows the detailed geology of the model domain as well as the outline of the simulated magma chamber and the location of calculated model results.

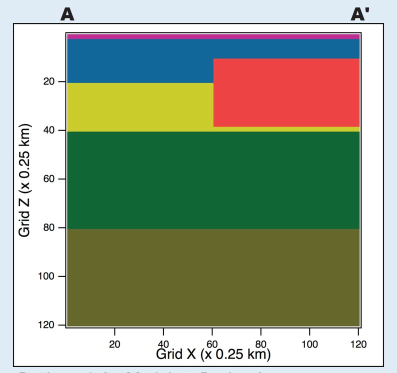
The Timber Mountain caldera complex has been extensively studied and its geologic history is well-established (Byers et al., 1976; Christiansen et al., 1977). There have been four major eruptions of ash-flow tuff, resulting in a series of nested calderas. These four major eruptions span the time interval from 12.8 to 11.5 Ma; each of these eruptions is estimated to be about 1000 km^3 in volume. This indicates that the magma chambers that produced each of these huge eruptions were on the order of 5000 to 10,000 km^3 (Smith, 1979). In all of the models presented here (Table 1), a magma chamber volume of 5000 km^3 is simulated.

Figure 4

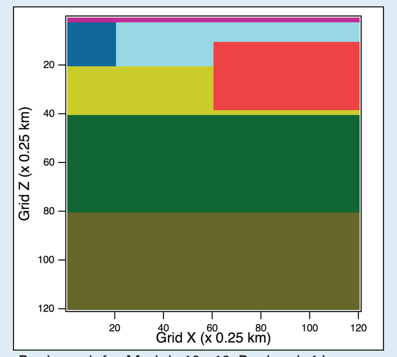


Geologic map of the 60 x 60 km model domain (extracted from Slate et al., 1999) showing the model outline of the simulated magma chamber and the point on Yucca Mountain (8 km from the edge of the Timber Mountain caldera complex) where model results are shown. Cross section A-A' is an example location for the model half-space cross sections shown in Fig. 5.

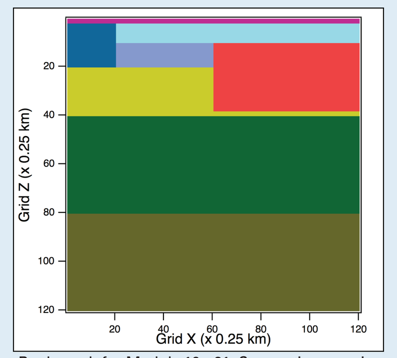
Figure 5



Rock mesh for Model 15. Rock units are numbered 1 through 5 from base to top; the magma chamber is shown in red. There is a mirror-plane on the right-hand side.



Rock mesh for Models 16 - 18. Rock unit 4 is divided into convective (inboard) and non-convective (outboard) zones.



Rock mesh for Models 19 - 21. Convective zone is further subdivided into an upper and lower zone.

Table 1. Model Parameters and Results

Model No.	Start Time	Grid Spacing	Magma Volume	Depth to Chamber	Magma Type	Convection Locus	Porosity & Timing	Model Results
10	11 Ma	0.5 km	5000 km^3	5 km	rhyolitic (900 °C)	Conduction only	NA	Does not match thermal history unless the locus of the magma chamber is closer to YM site than indicated by location of caldera.
11	15 Ma	0.5 km	5000 km^3	5 km	rhyolitic (900 °C)	Conduction only	NA	Does not match thermal history unless the locus of the magma chamber is closer to YM site than indicated by location of caldera.
12	15 Ma	0.5 km	5000 km^3	5 km	rhyolitic (900 °C)	Conduction only	NA	Does not match thermal history unless the locus of the magma chamber is closer to YM site than indicated by location of caldera.
13	15 Ma	0.5 km	5000 km^3	5 km	rhyolitic (900 °C)	Above chamber	20%	Does not match thermal history unless the locus of the magma chamber is closer to YM site than indicated by location of caldera.
14	15 Ma	0.5 km	5000 km^3	2.5 km	rhyolitic (900 °C)	Above chamber	20%	Does not match thermal history unless the locus of the magma chamber is closer to YM site than indicated by location of caldera.
15	12.8 Ma	0.25 km	5000 km^3	2.5 km	rhyolitic (900 °C, replenished at 11.6 Ma)	Rock unit 4	20%, ended at 10 Ma	Model did not run to completion.
16	12.8 Ma	0.25 km	5000 km^3	2.5 km	andesitic (1000 °C, replenished at 11.6 Ma)	Rock unit 4 adjacent to and above chamber	20%, ended at 10 Ma	Cools extremely fast once convection ends.
17	12.8 Ma	0.25 km	5000 km^3	2.5 km	andesitic (1000 °C, replenished at 11.6 Ma)	Rock unit 4 adjacent to and above chamber	20%	Model results in excessively warm conditions at young ages.
18	12.8 Ma	0.25 km	5000 km^3	2.5 km	andesitic (1000 °C, replenished at 11.6 Ma)	Rock unit 4 adjacent to and above chamber	10%	Model results in excessively warm conditions at young ages.
19	12.8 Ma	0.25 km	5000 km^3	2.5 km	andesitic (1000 °C, replenished at 11.6 Ma)	Rock unit 4 adjacent to and above chamber	10%, 5% @ 10 Ma, 2% @ 9 Ma, ended at 8 Ma	Close to matching data, cools rapidly at 8 Ma.
20	12.8 Ma	0.25 km	5000 km^3	2.5 km	andesitic (1000 °C, replenished at 11.6 Ma)	Reduced vertical extent of convecting zone	10%, 5% @ 10 Ma, 2% @ 9 Ma, ended at 8 Ma	Similar but reaches lower maximum temperatures.
21	12.8 Ma	0.25 km	5000 km^3	2.5 km	andesitic (1000 °C, replenished at 11.6 Ma)	Convection in deeper portion ended at 10 Ma	10%, 5% @ 10 Ma, 2% @ 9 Ma, ended at 8 Ma	Judged to be close enough to matching data that no more models were constructed.

Table 2. Rock Units

Depth Range	Number	Unit	ρ (kg/m3)	C (J/kg K)	k (W/m K)	Notes
20 - 30 km	1	metamorphic rocks	3300	980	2.0	
10 - 20 km	2	mafic igneous rocks	2850	980	3.0	
5 - 10 km	3	carbonate rocks	2650	980	1.0	
0 - 5 km	4	volcanic rocks	1750	980	1.3	portions of this rock unit are convective in models 14 - 21
0 - 0.5 km	5	UZ volcanic rocks	1900	980	1.0	beginning in model 12

DOCUMENTATION OF THERMAL MODELING

Models 15 - 21 were constructed using HEAT3D (version 4.10.0517; Wohletz and Heiken, 1992; Wohletz et al., 1999) in 2005. Table 1 shows the key model parameters and results for all models. The goal of these modeling exercises was to put as much realism into the models as possible and to investigate the effects of hydrothermal convection outboard from the magma chamber. Each of these models assumes the presence of an additional 100 m of Rainier Mesa Tuff deposited on the older tuffs at 11.6 Ma, eroded linearly through time.

Model 15 uses a 2D simulation of a 30 x 30 km grid (total model is symmetric about the central plane so only half the space needs to be considered). The grid spacing was set to 0.25 km using a mirror on the right-hand side. The rock mesh is shown in Figure 5 and the rock unit properties are listed in Table 2. These models all start at 12.8 Ma rather than 15 Ma used in previous models. This was done to eliminate the unrealistic assumption of the continuous presence of magma in the chamber from 15 to 11 Ma. The model begins with the emplacement of magma at the initiation of the Paintbrush Group eruptives. The magma chamber is replenished with fresh magma at 11.6 Ma, corresponding to the approximate time of the Timber Mountain Group eruptives. Hydrothermal convection in unit 4 was allowed until 10 Ma. Magma advection calculation and acceleration were turned off. The time step and dump interval were 53.3 years and 53,344 years, respectively. The simulation continued until 6.5 m.y. after 99 dump intervals. Model results are shown in Figure 6 for a location 8 km outside the caldera wall (see Fig. 4) at depths of 100 to 200 m, corresponding to the general locations of samples used to reconstruct the thermal history.

Model 16 employed refinements to Model 15 to allow for longer time runs and restrict hydrothermal convection near the edge (within 5 km) of the model space. Watch Points were set to monitor the surface thermal gradient at the edge of the caldera (x = 60), and at 4 km (x = 22) and 8 km (x = 28) from the caldera. Andesitic composition magma properties were employed (rather than rhyolitic as was used in earlier models). The initial time step for Model 16 was 107 years with a dump interval set to 99,966 years. At 10 Ma, hydrothermal convection was disallowed; this increased the time step to 184 years.

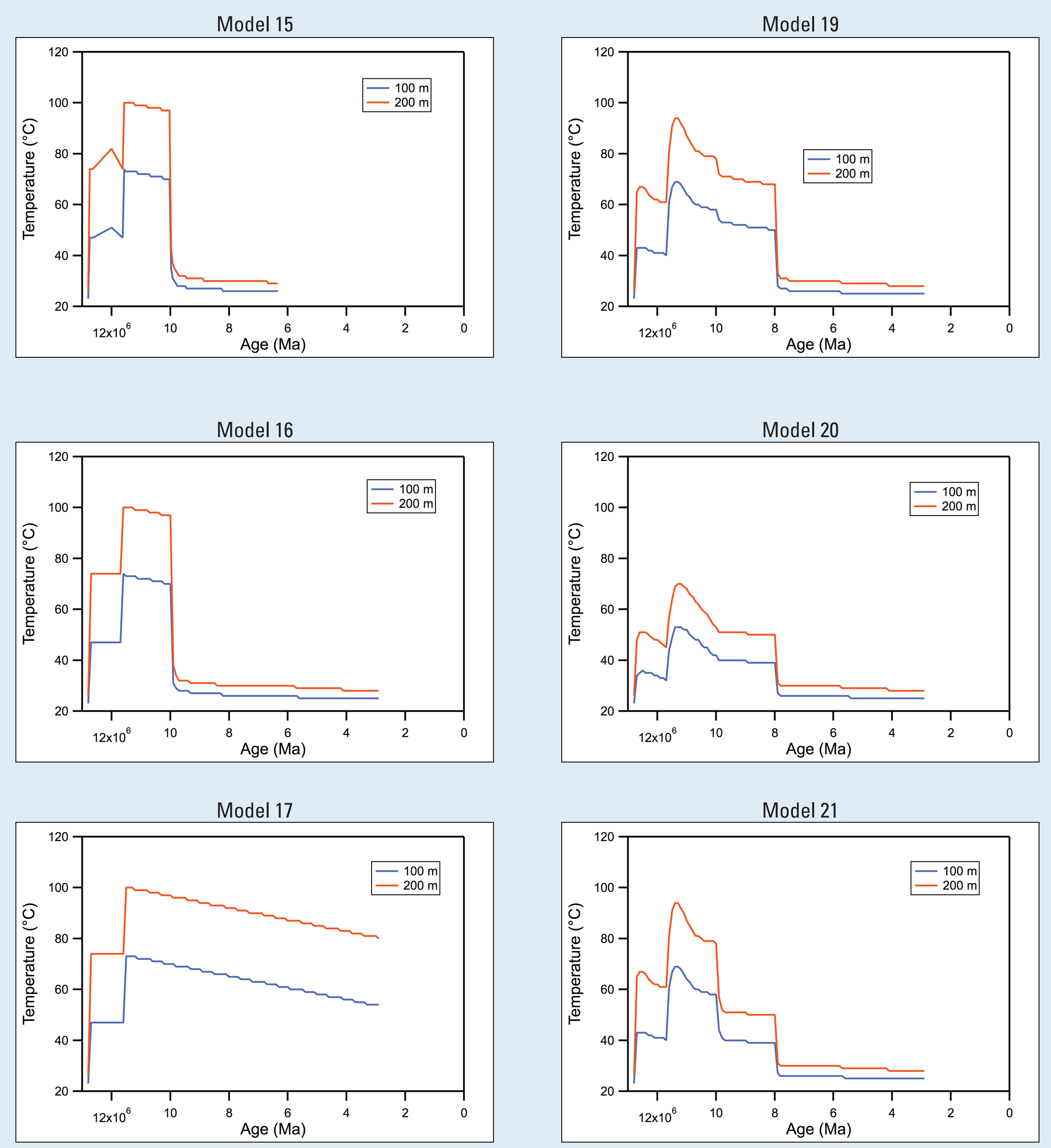
Model 17 was identical to Model 16, but hydrothermal convection was allowed to continue rather than stopping at 10 Ma. This had the effect of prolonging high temperatures above the zone of hydrothermal convection. This model did not cool down. In Model 18, hydrothermal convection also was allowed to continue, but the porosity in the convecting unit was reduced to 10%. Model 18 also does not cool down (not shown).

In Model 19, the porosity of the convecting unit was reduced at different times to simulate the effect of the clogging of pores by secondary minerals such as quartz. The porosity started out as 10%, but was reduced to 5% at 10 Ma, to 2% at 9 Ma and then hydrothermal circulation was disallowed at 8 Ma.

Because hydrothermal convection results in nearly constant temperature with depth in the convective zone, artificially high temperatures may result from deep convective flow. Therefore, Model 20 reduced the vertical extent of the convective zone. All other parameters were kept the same as in Model 19. The time step starts out at 213 years, increases to 311 years at 10 Ma (after first reduction in porosity), and then decreases to 184 years at the end of the convective period (8 Ma).

Model 21 starts out with the full extent of the original convective zone, but changes the deeper portion to conduction only at 10 Ma. In the upper portion of the convective zone, porosity is reduced with time as before: 5% at 10 Ma and 2% at 9 Ma. After 8 Ma, only conductive cooling is allowed.

Figure 6



The HEAT3D code provides graphic and data output at predetermined intervals. Figure 7 shows the surface thermal gradients across the model domain at 10 Ma and Figure 8 shows the temperatures in the model grid at 10 Ma, both for Model 21. These figures show a somewhat lower temperature region above the magma chamber than adjacent to the chamber due to hydrothermal convection beneath the unsaturated zone, similar to the hydrothermal outflow plume proposed by Bish and Aronson (1993).

Figure 7

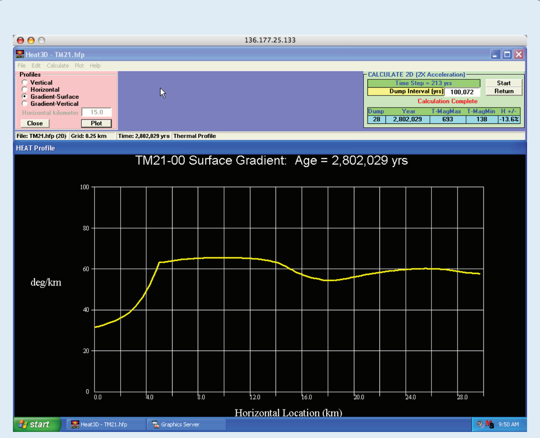


Figure 8

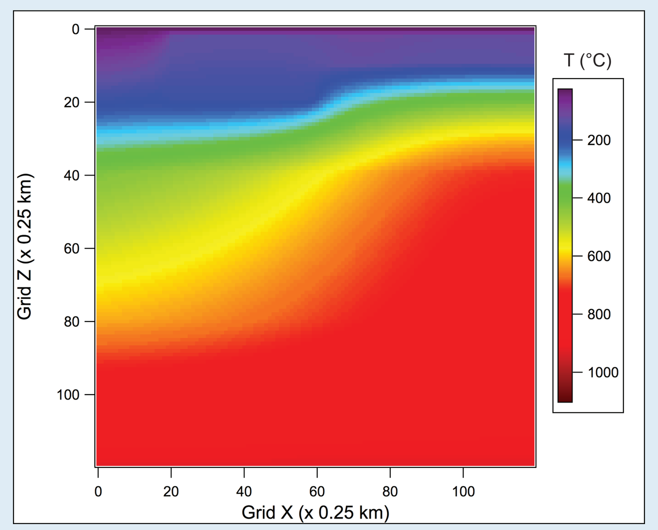
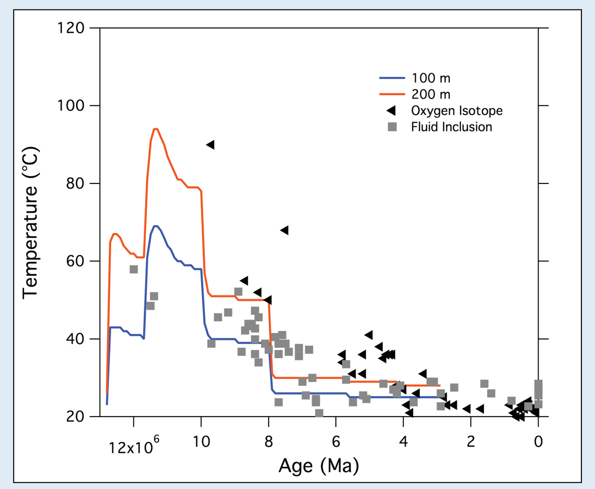


Figure 9



CONCLUSIONS

1. The simulations of the thermal evolution of the Timber Mountain caldera complex indicate that the inferred cooling history of the unsaturated zone at Yucca Mountain can be explained by the slow cooling of a subvolcanic batholith. The Model 21 results match the thermal history data adequately (Fig. 9), considering the simplicity of, and assumptions in, the model and uncertainties in the data.
2. The thermal histories simulated by the various models show large variations depending primarily on the locus and timing of hydrothermal activity in rocks beneath the unsaturated zone.
3. Additional constraints on the size and geometry of the magma chamber as well as additional thermochronologic measurements would enhance future model realizations; a greater volume of magma could, for example, amplify thermal gradients and prolong increased temperatures in in the UZ.
4. The results of these types of finite-difference numerical models must be carefully evaluated considering the imposed simple geometry and symmetry; the actual thermal regime around a caldera is not likely to be symmetrical, e.g. heat flow around the Valles caldera (Morgan et al., 1996).
5. In addition to post-volcanic hydrothermal outflow as discussed in Bish and Aronson (1993), further magma flux into the subcaldera chamber likely continued for some time after the final volcanic eruptions (Jellinek and DePaolo, 2003), adding to the magnitude and length of the thermal pulse.

CRITICISMS

Dublyansky and Polyansky (2007) performed additional modeling efforts and concluded that their models could not reproduce the thermal history. Dublyansky (2014) did reproduce the model presented in Whelan et al. (2008) but concluded the model was not valid. His main criticisms and our responses are outlined below.

- Rock mesh is unrealistic because the outlying block of volcanic rock is designated as impermeable.
  The model domain must contain the heat generated by the emplaced magma. There is no recharge or discharge in the model; convective zones are closed cells in which upward flow and downward flow are allowed.
- Movement of fluids were not realistically reproduced due to limitations of the code.
  This limitation is acknowledged; the model is primarily a conductive model and has been applied to other similar scenarios, albeit at shorter time scales.
- Magma advection and rock displacement upon magma replenishment is not realistic.
  Again, the limitation of the model is evident. However, the imposition of sudden changes in magma intrusion is typical in these types of simulations. The discussion of magma advection is confusing and does not apply universally because this option was not enabled in all models.
- UZ thickness is incorrect.
  Although a 750 m-thick UZ could have been modeled, the choice of 500 m is conservative; also the additional 100 m of overburden at Timber Mountain time is included.
- Conservativeness of the modeled magma chamber questioned.
  The simulations utilized a magma volume of 5000 km^3, rather than assuming a more typical estimated volume of 10000 km^3 based on the eruptive volumes of the three main ash-flow tuffs. The depth to the top of the solidified pluton, estimated from geophysical measurements, is used as the simulated top of the magma chamber.
- The HEAT3D code was not qualified for use on the Yucca Mountain Project.
  The thermal modeling task was not part of the performance assessment, but was performed in order to provide a more complete understanding of the ancient thermal history of the site (see Houseworth and Hardin, 2010).
- No modeling outcomes produce a reasonable match with the empirical benchmark data.
  We think that we have shown that the model, given its limitations and uncertainties, does provide a reasonably close approximation to the known thermal history, which is also limited by uncertainties.

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