Prepared in cooperation with the
U.S. Department of Energy,
Office of Repository Development, under
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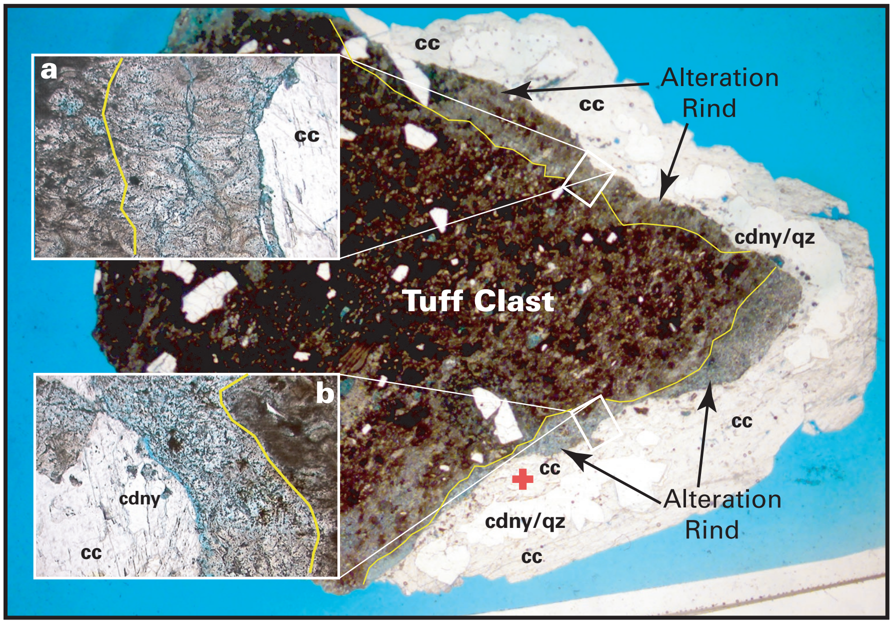
Secondary Mineral Deposits and Evidence of Past Seismicity and Heating of the Proposed Repository Horizon at Yucca Mountain, Nevada



Water-Resources Investigations Report 03–4321

U.S. Department of the Interior
U.S. Geological Survey

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Gale A. Norton, Secretary

U.S. Geological Survey
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Conversion Factors, Standards, Acronyms, and Abbreviations

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Stable isotope compositions are reported as delta (δ) values in units of parts per thousand (denoted as per mil or ‰) relative to a standard of known composition: Pee Dee Belemnite (PDB) for carbon (C), and Standard Mean Ocean Water (SMOW) for oxygen (O) (Craig, 1961).

DDA	Drift Degradation Analysis
ECRB	Enhanced Characterization of the Repository Block
ESF	Exploratory Studies Facility
Ma	million years ago
m.y.	million years
Pb	lead
U	uranium
USGS	U.S. Geological Survey
UZ	unsaturated zone

Secondary Mineral Deposits and Evidence of Past Seismicity and Heating of the Proposed Repository Horizon at Yucca Mountain, Nevada

By Joseph F. Whelan

Abstract

The Drift Degradation Analysis (DDA) (BSC, 2003) for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, describes model simulations of the effects of pre- and post-closure seismicity and waste-induced heating on emplacement drifts. Based on probabilistic seismic hazard analyses of the intensity and frequency of future seismic events in the region (CRWMS M&O, 1998), the DDA concludes that future seismicity will lead to substantial damage to emplacement drifts, particularly those in the lithophysal tuffs, where some simulations predict complete collapse of the drift walls.

Secondary mineral studies conducted by the U.S. Geological Survey since 1995 indicate that secondary calcite and silica have been deposited in some fractures and lithophysal cavities in the unsaturated zone (UZ) at Yucca Mountain during at least the past 10 million years (m.y.), and probably since the tuffs cooled to less than 100°C. Tuff fragments, likely generated by past seismic activity, have commonly been incorporated into the secondary mineral depositional sequences.

Preliminary observations indicate that seismic activity has generated few, if any, tuff fragments during the last 2 to 4 m.y., which may be inconsistent with the predictions of drift-wall collapse described in the DDA. Whether or not seismicity-induced tuff fragmentation occurring at centimeter to decimeter scales in the fracture and cavity openings relates directly to failure of tuff walls in the 5.5-m-diameter waste emplacement drifts, the deposits do provide a potential record of the spatial and temporal distribution of tuff fragments in the UZ. In addition, the preservation of weakly attached coatings and (or) delicate, upright blades of calcite in the secondary mineral deposits provides an upper limit for ground motion during the late stage of deposition that might be used as input to future DDA simulations. Finally, bleaching and alteration at a few of the secondary mineral sites indicate that they were subjected to heated gases at approximately the temperatures expected from waste emplacement. These deposits provide at least limited textural and mineralogic analogs for waste-induced, high-humidity thermal alteration of emplacement drift wall rocks.

Introduction

Performance objectives for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, require waste containment for a minimum of 10,000 years (fig. 1). As a result, the long-term stability of emplacement drifts and the potential consequences of drift wall collapse on waste containment are central to assessments of site performance. The Drift Degradation Analysis (DDA) (BSC, 2003) describes model simulations of the effects of pre- and post-closure seismicity and waste-induced heating on (1) tuff fragmentation and the possible collapse of drift walls, (2) stress distribution in the drift wall rocks, and (3) possible alteration of fracture surfaces (weathering/rock joint degradation) produced by heating at high water-vapor pressures. Using probabilistic seismic hazard analyses of the intensity and frequency of future seismic events in the region (CRWMS M&O, 1998), the DDA concludes that post-closure seismicity will lead to substantial damage to emplacement drifts, particularly those in the lithophysal tuffs, where some simulations predict complete collapse of the drift walls.

Since 1995, the U.S. Geological Survey (USGS), in cooperation with the U.S. Department of Energy, has studied deposits of secondary calcite and silica in the tuffs. These deposits, located in centimeter to decimeter scale fractures and cavities in the unsaturated zone (UZ) rock at Yucca Mountain, contain evidence of past seismic and heating events. Whether or not seismicity-induced tuff fragmentation occurring in fracture and cavity openings relates directly to failure of tuff walls in the 5.5-m-diameter emplacement drifts, the deposits do provide a potential record of the spatial and temporal distribution of tuff fragmentation in the UZ and an upper limit for ground motion during the late stage of secondary mineral deposition. The existing archive of more than 400 samples of secondary mineral deposits collected by the USGS from underground

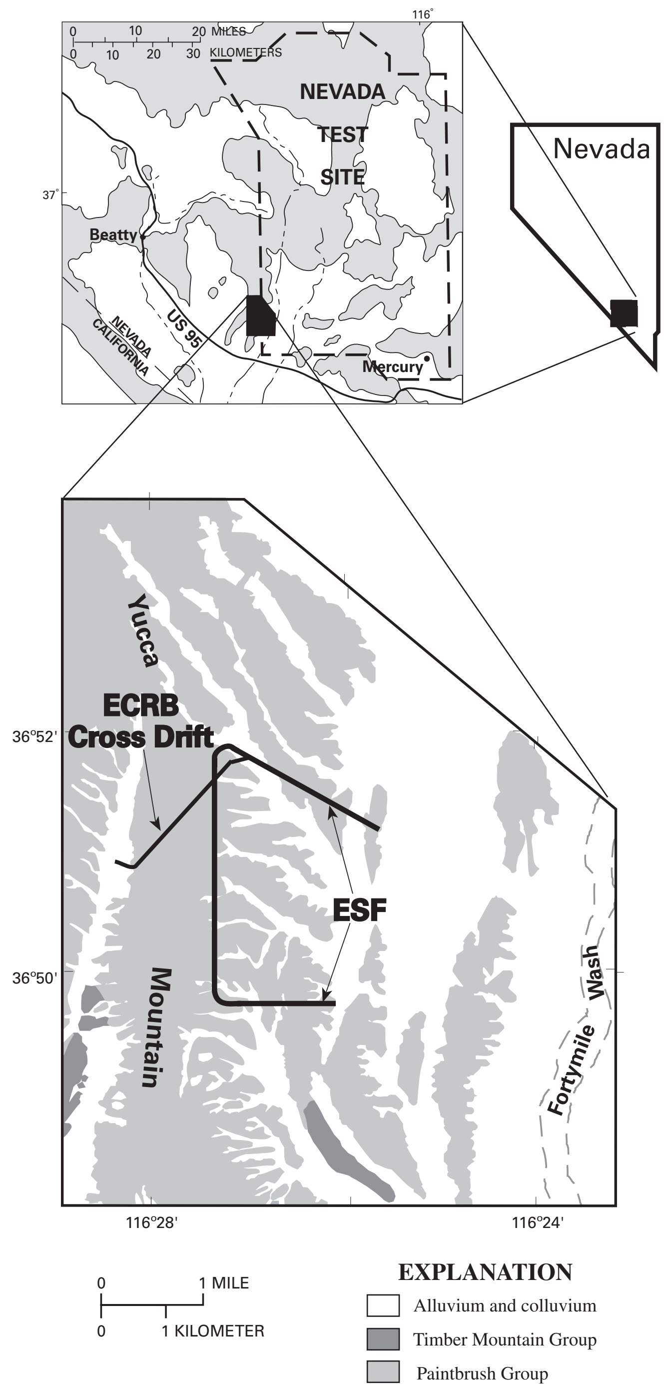


Figure 1. Location of Yucca Mountain, Nevada, and the Exploratory Studies Facility (ESF) and Enhanced Characterization of the Repository Block (ECRB) Cross Drift tunnels, with surficial geology generalized from Day and others (1998). The distribution of Quaternary valley fill (white) and bedrock (shaded) are shown in the upper map.

exposures in the Exploratory Studies Facility (ESF) and Enhanced Characterization of the Repository Block (ECRB) Cross Drift (fig. 1) would permit reconstruction of this record.

The DDA also addresses the alteration (rock joint degradation and loss of fracture surface contact cohesion) of tuff surfaces that could result from the moist and warm (140 to 160°C) conditions following waste emplacement. Weak alteration observed on some fracture surfaces associated with a few of the secondary mineral deposits, possibly related to the waning stages of the initial cooling of the tuffs, may provide an analog for waste-induced thermal alteration.

This report describes observations made during the course of the USGS studies that relate to records of past seismicity and heating of the UZ. Site geology, secondary mineral deposits, and thermal history are summarized and evidence of past seismicity and heating is described.

Site Geology

The proposed high-level radioactive waste repository at Yucca Mountain would be constructed in the thick UZ in the Topopah Spring Tuff of the Paintbrush Group rhyolitic to quartz dacitic tuffs. The Miocene-age Paintbrush Group (12.8 to 12.7 million years ago [Ma], Sawyer and others, 1994) consists of two 200- to 300-m-thick, largely welded tuffs, the Tiva Canyon Tuff (younger) and the Topopah Spring Tuff (older), which are separated by a thin (~50 m) sequence of nonwelded and weakly fractured bedded tuffs (Moyer and others, 1996).

The Topopah Spring Tuff has been divided into zones, primarily distinguished by the presence or absence of lithophysal cavities that formed from and were altered by gases that exsolved during the initial cooling of the tuffs (Buesch and others, 1996). Waste emplacement drifts would be located in the upper lithophysal (Tptpul), middle nonlithophysal (Tptpmnl), and lower lithophysal (Tptpll) zones.

Secondary Mineral Deposits

Vapor-Phase and Fumarolic Mineral Deposition

The earliest secondary mineralization in the tuffs was from hot gases that exsolved during initial cooling of the tuffs. Fracture and lithophysal cavity walls were altered by these gases, which also deposited vapor-phase minerals consisting largely of tridymite or cristobalite, sanidine, and minor amounts of hematite, biotite, and garnet (Vaniman and others, 1984). Fumaroles occurred near the tops of the Tiva Canyon and Topopah Spring Tuffs, with clay, zeolitic, and (or) silicic alteration and deposition of minor amounts of drusy quartz and fluorite on some fractures (Levy and others, 1996). As the tuffs cooled, weak or waning fumarolic systems may have deposited calcite and silica at near-boiling temperatures on the surfaces of some fractures in the Tiva Canyon Tuff (Whelan and others, 2003).

Low-Temperature Secondary Mineral Deposition

Calcite and silica (quartz, chalcedony, and opal) with minor amounts of fluorite, zeolites, and manganese oxides are found in some open fractures and lithophysal cavities in the Topopah Spring and Tiva Canyon Tuffs in the UZ (Whelan and others, 1994; Paces and others, 2001; Whelan and others, 2002). Reconnaissance studies of these deposits from drill core samples indicate that the secondary minerals formed in the UZ from meteoric waters percolating along fractures to the water table (Szabo and Kyser, 1990). This interpretation is supported by textural and geochemical studies of pedogenic calcrete in soils and fault-infillings at the surface (Quade and Cerling, 1990; Stuckless and others, 1991; U.S. Department of Energy, 1993; Vaniman and others, 1994; and Vaniman and Whelan, 1994) that demonstrate a clear link between pedogenic deposition in the overlying soils, infiltration of meteoric water, and secondary mineral deposition in the UZ (Whelan and others, 1994; Paces and others, 2001).

Further evidence that secondary mineral deposition in the UZ occurred under vadose conditions is provided by underground exposures in the ESF and ECRB Cross Drift. These exposures show the deposits are sparsely and heterogeneously distributed on less than 10 percent of potential fracture and cavity depositional sites, and are generally restricted to the floors of lithophysal cavities and the footwalls of fractures in the welded tuffs (Paces and others, 2001; Whelan and others, 2002).

The secondary mineral deposits range in thickness from a fraction of a millimeter to as much as 5 cm. Typical coatings are 5 to 10 mm thick in cavities and 1 to 5 mm thick on fractures. Secondary mineral deposits on fracture footwalls tend to form coatings of relatively uniform thickness or masses of calcite-cemented fracture (or fault) breccia. On the floors of lithophysal cavities, the deposits are coarser grained and commonly contain elongate, thin blades of calcite.

Based on visual examination of samples, the generalized paragenetic sequence of secondary mineral deposition in the UZ is divided into early, intermediate, and late stages (Whelan and others, 2002). The early stage consists of calcite, followed by calcite that is locally admixed with fluorite and commonly capped by deposition of thick (up to about 1 cm) layers of botryoidal chalcedony and (or) drusy quartz. Where present, this layer of silica minerals marks the end of the early stage. The intermediate and late stages are mineralogically similar, but the textures are different. Both consist mainly of calcite and opal (although minor amounts of chalcedony may be found in the basal part of the intermediate stage). Intermediate-stage calcite typically displays an elongate, thin-bladed habit, whereas late-stage calcite typically forms overgrowths on older calcite, often as distinctive knobby or corniced masses on the tips of intermediate-stage blades. Intermediate- and late-stage opal forms botryoidal masses and laminar sheets on or interlayered with calcite (Whelan and others, 2002).

Thermal History

The post-eruptive thermal history of the UZ tuffs has been determined by combined oxygen isotope, fluid inclusion, and uranium-lead (U-Pb) dating studies of secondary minerals from deposits found in the ESF and ECRB Cross Drift (Whelan and others, 2001; Whelan and others, 2002; Neymark and others, 2003; Wilson and others, 2003). Although the UZ calcite is not amenable to U-Pb dating, chalcedony and opal provide reliable $^{207}Pb/^{235}U$ ages and, where closely associated with calcite whose depositional temperature could be estimated from fluid inclusions or $\delta^{18}O$ values, provide the age framework for the thermal history of the UZ. Figure 2 shows depositional temperatures of calcite in deposits from the ESF and ECRB Cross Drift, determined from fluid-inclusion homogenization temperatures (triangles or diamonds) or estimated from $\delta^{18}O$ values (circles) and the $^{207}Pb/^{235}U$ ages (±2 sigma) of chalcedony or opal associated with the calcite. For determinations that are a minimum age of calcite deposition (triangles and some circles), the true age of the calcite deposition lies somewhere along the tie lines (dotted) connecting the measured age to the eruptive age of the Paintbrush Group tuffs. Diamonds and most circles represent calcite whose depositional age is tightly constrained by opal or chalcedony age determinations. Temperatures were calculated from the $\delta^{18}O$ value of calcite (circles) assuming a $\delta^{18}O$ value of –11 per mil (‰) for the depositing water. Best-fit curves are shown for depositional waters having $\delta^{18}O$ values of –13, –11, and –9‰. This thermal history indicates that the early stage ended about 8 Ma with depositional temperatures of 50 to 90°C. Depositional temperatures then slowly decreased during the intermediate stage to present-day ambient temperatures of 20 to 25°C, which have prevailed for the past 2 to 4 million years (m.y.), through deposition of the late-stage minerals (Whelan and others, 2001, 2003; Wilson and others, 2003).

The $\delta^{13}C$ values of calcite constrained by $^{207}Pb/^{235}U$ ages of chalcedony or opal are shown in figure 3. Where the associated chalcedony or opal provides only a minimum or maximum estimate of the age of the calcite, an arrow points in the direction of the true age of the calcite. Approximate time boundaries separating the early, intermediate, and late stages of deposition are shown. Calcite $\delta^{13}C$ values decrease steadily from the early stage, where values commonly exceed +4‰, through the intermediate stage to the late stage, where they are generally less than –4‰. This time-dependent decrease allows

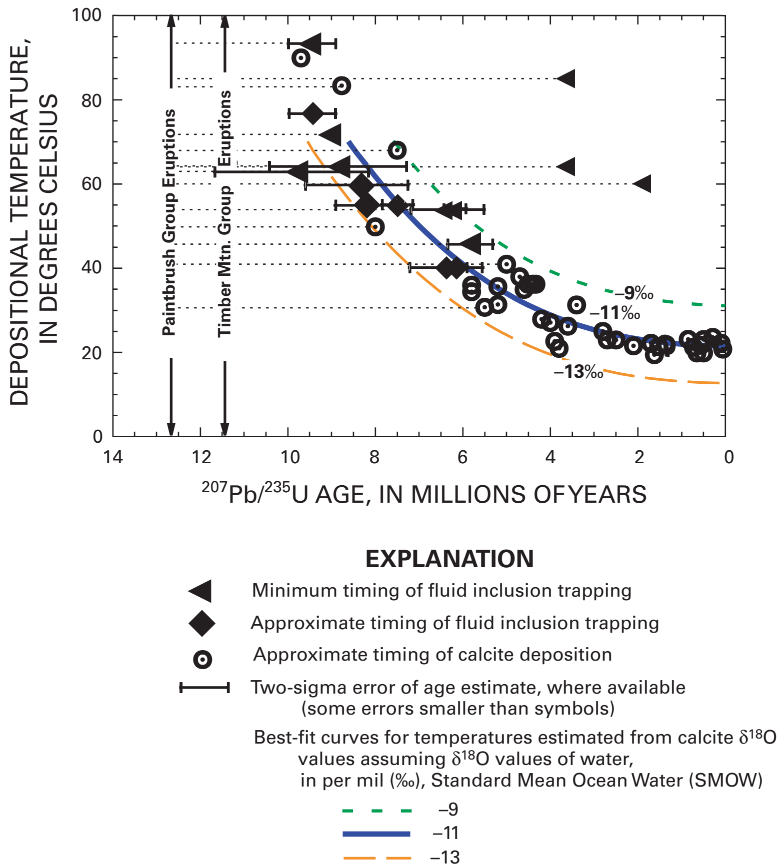


Figure 2. Depositional temperatures and timing of secondary calcite from deposits in the Exploratory Studies Facility (ESF) and Enhanced Characterization of the Repository Block (ECRB) Cross Drift tunnels. Temperature estimated from fluid inclusions or calcite $\delta^{18}O$ values and timing estimated from the $^{207}Pb/^{235}U$ ages of chalcedony or opal associated with the calcite (modified from Whelan and others, 2003).

general inferences of the timing of deposition from the $\delta^{13}C$ values of calcite. Figure 4 shows the $\delta^{13}C$ values of calcite decreasing and the $\delta^{18}O$ values increasing from the early to the late stages. Basal, intermediate, and outer positions were determined by petrographic examination and generally correspond to the early, intermediate, and late paragenetic stages. The $\delta^{13}C$ and $\delta^{18}O$ values, combined with the textural and mineralogical characteristics of the different stages and age- $\delta^{13}C$ relations shown in figure 3, permit $\delta^{13}C$ and $\delta^{18}O$ studies of individual samples to be correlated with the age framework of calcite deposition.

Evidence of Past Seismicity and Heating

The secondary mineral deposits record not only the thermal history of the UZ but also, by their textures, local records of tuff fragmentation (breccia deposits) in faults, fractures, and lithophysal cavities. In addition, the survival of weakly attached coatings and (or) delicate mineral textures may provide an estimate of past peak ground motions in the rocks in the proposed repository. Finally, alteration and bleaching of the fracture walls of some deposits may present an analog for the weathering effects of hot, water-saturated air on tuff surfaces.

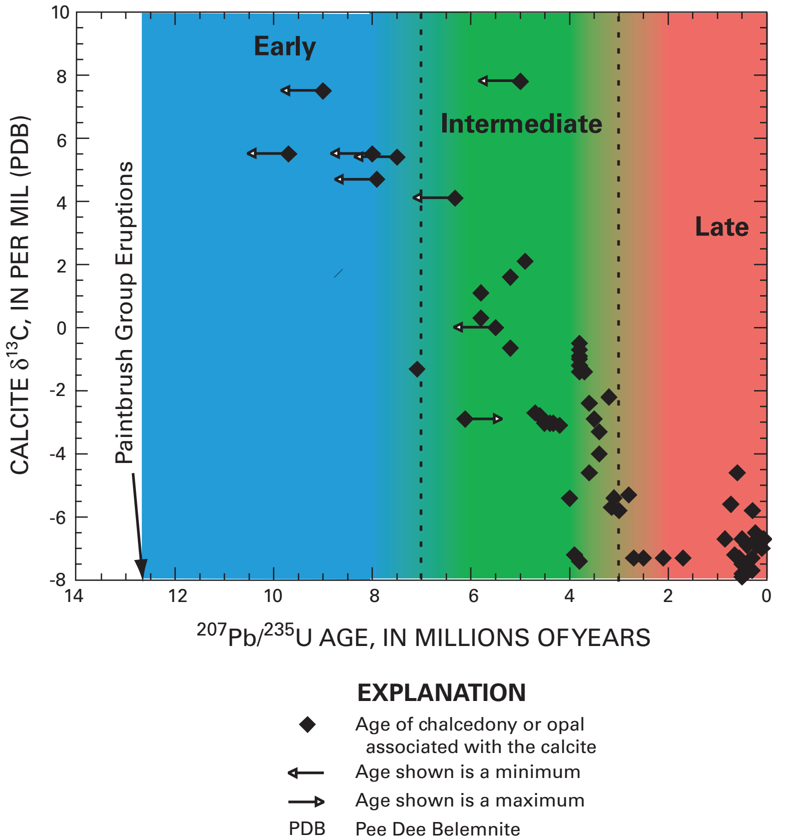


Figure 3. Changes in calcite $\delta^{13}C$ values with paragenetic stage for samples from the Exploratory Studies Facility (ESF) and Enhanced Characterization of the Repository Block (ECRB) Cross Drift tunnels (modified from Whelan and Moscati, 1998).

Tuff Fragmentation

As secondary mineral coatings formed, some incorporated tuff fragments. In faults and fractures, these fragments generally came from higher in the rock mass and they record the availability of loose tuff fragments and (or) past seismic activity that may have generated or dislodged loose material. Secondary mineral deposits may incorporate such tuff fragments (fig. 5) or cement them in fault or fracture breccias (fig. 6). Figure 5 shows a secondary mineral coating with included tuff fragments from a lithophysal cavity at ECRB Cross Drift station 10+10. The paragenetic boundaries between the early, intermediate, and late stages of deposition are delineated in red. Calcite $\delta^{13}C$ and $\delta^{18}O$ values range from –6.4 to 4.8‰ and from 14.6 to 16.2‰, respectively, and are consistent with the paragenetically constrained ranges shown in figure 4. Angular fragments of tuff ranging in size from less than a millimeter to more than a centimeter, as shown in the sample from ECRB Cross Drift station 10+10, are common in early-stage calcite and rare in intermediate- and late-stage calcite. Impregnation with blue-dyed epoxy distinguishes primary porosity. Figure 6 shows calcite cementation of a fault breccia at ESF station 76+17.6. This cemented breccia fills a near-vertical fault opening that is about 10 cm wide. Paragenetic relations in cemented breccias are generally ambiguous, even at the small scale of a petrographic section. Calcite $\delta^{13}C$ and $\delta^{18}O$ values range from –6.4 to 2.5‰ and from 14.0 to 18.3‰, respectively, and are consistent with the calcite $\delta^{13}C$ and $\delta^{18}O$ variations shown in figure 4.

In lithophysal cavities, tuff infall from the walls or ceilings into secondary mineral deposits provides a record of caving or scaling from the cavity walls that could have been in response to seismic shaking. In faults, fractures, and lithophysal cavities, these fragments generally range from less than a millimeter to several centimeters. In a few lithophysal cavities, larger fragments of the walls or ceilings fell and became cemented into deposits on the cavity floors. Although the distribution and frequency of fragment incorporation into the coatings has not been documented, general observations made during previous studies of samples from the ESF and

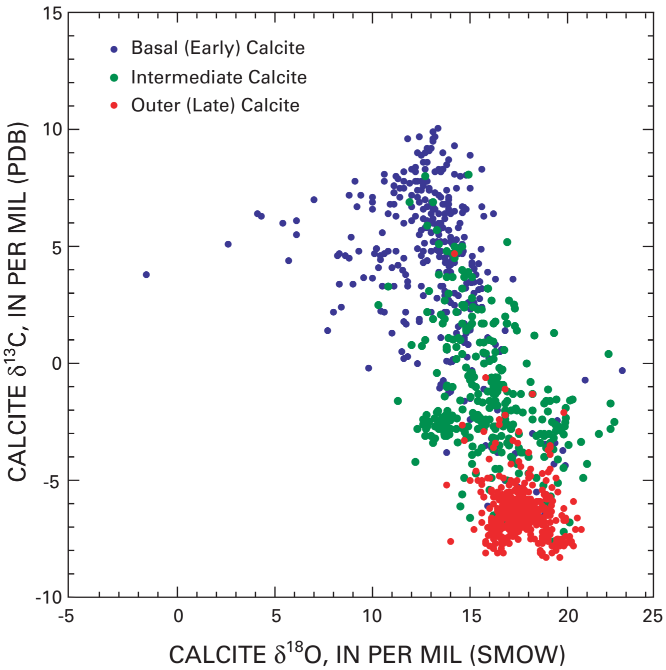


Figure 4. Values of $\delta^{13}C$ and $\delta^{18}O$ in calcite from locations in the Exploratory Studies Facility (ESF) and Enhanced Characterization of the Repository Block (ECRB) Cross Drift tunnels (modified from Whelan and others, 2002). Stable isotope standards are Pee Dee Belemnite (PDB) for carbon and Standard Mean Ocean Water (SMOW) for oxygen.

ECRB Cross Drift indicate that inclusion of tuff fragments was common during the early stage but became increasingly rare during the intermediate and late stages of secondary mineral deposition (fig. 5). These preliminary observations could be verified by systematic examination of the existing collection of samples and petrographic sections from the ESF and ECRB Cross Drift. Such data, combined with geochronologic, isotopic, and textural constraints, could be used to generate a map and history of tuff fragmentation in the UZ at Yucca Mountain.

Coating Displacement or Damage to Delicate Mineral Textures

Fracture coatings that are or were weakly attached to the fracture walls locally provide an additional, anecdotal indication of peak ground motions. Some fracture coatings observed in the ESF and ECRB Cross Drift were so weakly attached that they could be pried easily from the fracture wall with a knife or even removed by hand. Such in-place coatings provide a measure of the maximum intensity of past ground motions in the UZ.

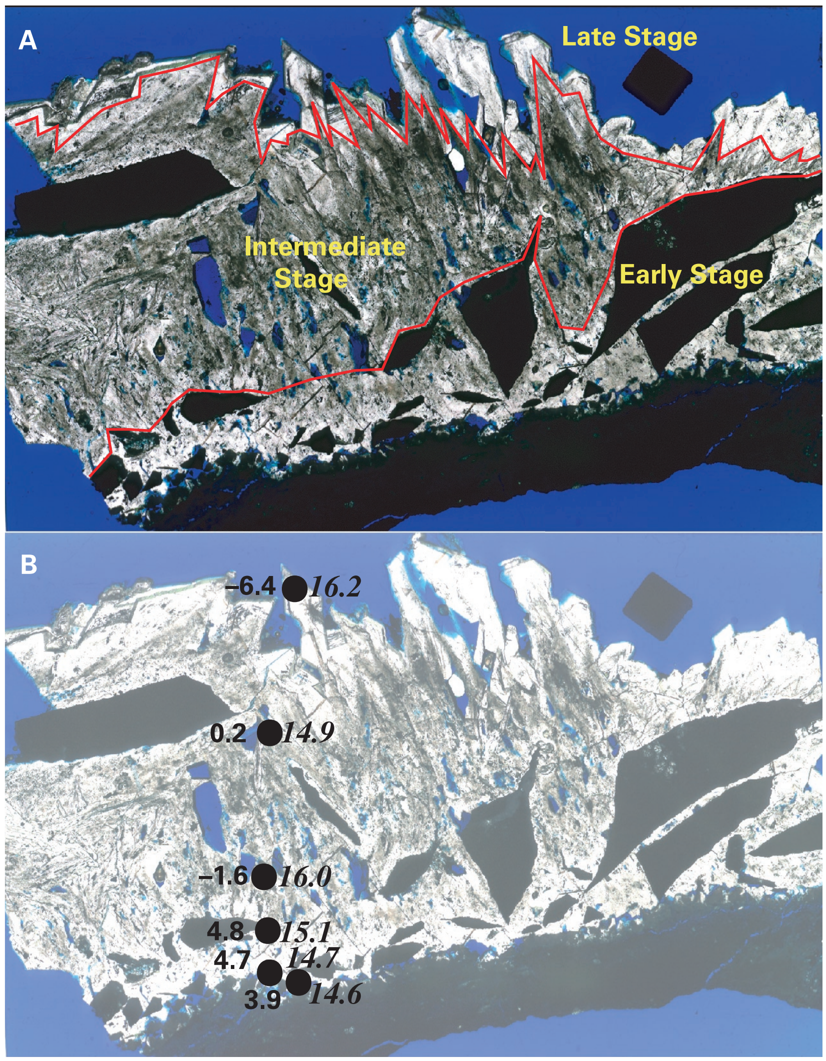
Some secondary mineral deposits contain fragments of fracture coatings that apparently have been dislodged from higher in the fracture, accumulated at a restriction, and then cemented together by later calcite deposition. Figure 7 shows a secondary mineral deposit at ESF station 52+43, from a steeply dipping fracture in the Topopah Spring Tuff, containing identifiable fragments of vapor-phase and calcite coatings. Although the high $\delta^{13}C$ values indicate that coating deposition began in the early stage, the $\delta^{13}C$ and $\delta^{18}O$ values of –6.7‰ and 18.4‰, respectively, are consistent with late-stage deposition and indicate that some of the coating displacement probably postdates 2 to 4 Ma. The paragenetic position of the calcite with $\delta^{13}C$ of 5.7‰ and $\delta^{18}O$ of 14.5‰ is uncertain but consistent with either the early or intermediate stage. Impregnation with blue-dyed epoxy distinguishes primary porosity. Combined isotopic and geochronological study of the secondary minerals could provide estimates of the timing of infall in such deposits.

Delicate, upright calcite blades with heights and widths of as much as 2 to 3 cm, but thicknesses less than a millimeter, are common. These delicate blades began forming during the intermediate stage and typically have top-heavy overgrowths of late-stage calcite and (or) opal that should increase their susceptibility to breaking during seismic shaking. Although the ground motion accelerations required to break such blades are unknown, broken crystals have not been observed in the deposits that have been studied. The preservation of these blades, therefore, provides an upper limit for ground motion during the late stage.

Surface maps of fault displacements at Yucca Mountain show that 12 seismic events producing displacements greater than 20 cm (with estimated magnitudes of 5.6 to 6.9) occurred during the last 500,000 years (CRWMS M&O, 2000, sec. 12.3.7.6). The average recurrence interval for these events is 44,000 years. However, late-stage secondary mineralization records little tuff fragment input or damage to the coatings that would be evidence for large-magnitude earthquakes. Although the open-space dimensions of UZ fractures and cavities are considerably smaller than the design dimensions of the emplacement drifts modeled in the DDA, the degree of tuff fragmentation and collapse predicted by the DDA from pre- and post-closure seismic and heating effects appears to be much greater than that recorded by the secondary mineral deposits.

Heating Effects and Alteration of Fracture Surfaces

The DDA (BSC, 2003) predicts maximum drift wall temperatures of 140 to 160°C within 100 years of waste emplacement, with concomitant thermal expansion stresses to the rocks and increased rates of weathering (alteration) of fracture walls. Secondary mineral fluid-inclusion studies show that the UZ was heated to temperatures of at least 50 to 70°C,



EXPLANATION

Approximate paragenetic stage boundary

Calcite subsample

3.9 $\delta^{13}C$ of calcite in per mil, PDB (Pee Dee Belemnite)

14.6 $\delta^{18}O$ of calcite in per mil, SMOW (Standard Mean Ocean Water)

Figure 5. Photomicrograph of a petrographic section of tuff fragments in a secondary mineral deposit from a lithophysal cavity in the Enhanced Characterization of the Repository Block (ECRB) Cross Drift tunnel at about station 10+10 showing: A, the secondary mineral paragenetic stages in transmitted plane light; and B, the same image showing the $\delta^{13}C$ and $\delta^{18}O$ values of calcite subsamples. Black square is approximately 2.3 millimeters wide.

and locally to at least 90°C, during the early stage (Whelan and others, 2003).

A few of the higher temperature (80 to 90°C) secondary mineral coatings, such as those observed at ESF station 1+62, have bleached and altered fracture and clast surfaces. This bleaching and alteration is not accompanied by deposition of vapor-phase minerals, such as tridymite or hematite, indicating that it postdates the highest temperature vapor-phase

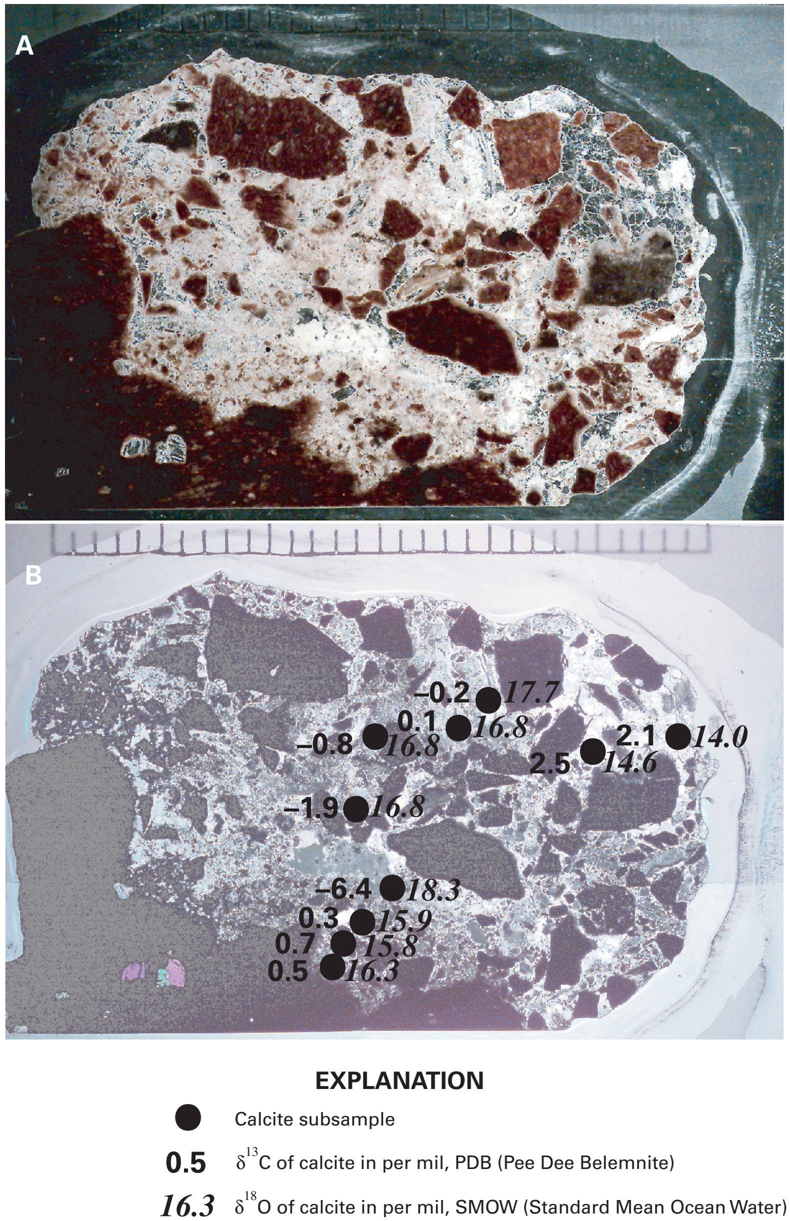
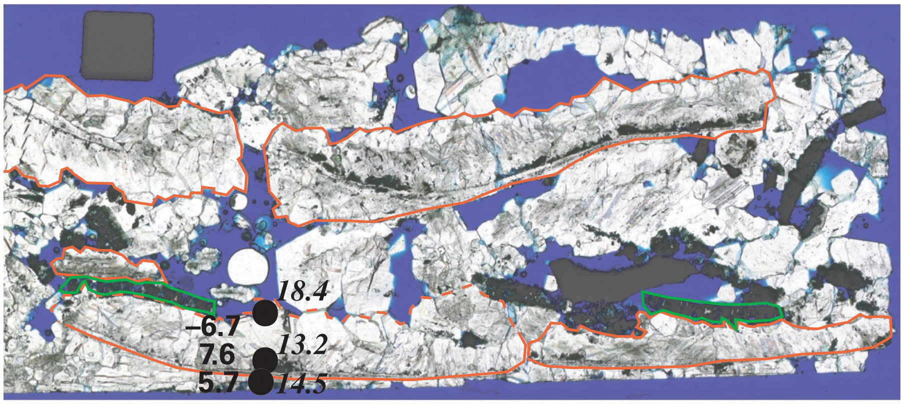


Figure 6. Photograph of a sawn and polished surface of tuff fragments in a calcite-cemented breccia from the Exploratory Studies Facility (ESF) tunnel at about station 76+17.6 showing: A, the breccia texture; and B, the $\delta^{13}C$ and $\delta^{18}O$ values of calcite subsamples. Scale bar is 3 centimeters.

alteration. Figure 8 shows early-stage calcite, chalcedony, and quartz, followed by intermediate- and late-stage calcite coatings on a tuff fragment from a near-vertical fracture at ESF station 1+62. In other sections from this site, calcite paragenetically equivalent to that calcite marked with a red "+" has fluid inclusion temperatures of 80 to 90°C and low $\delta^{18}O$ values of 3 to 5‰ that are consistent with elevated temperatures. The tuff fragment has thin rinds of bleaching and alteration beneath the secondary minerals. At higher magnification (50X), the rind shown in the inset photomicrograph (a) is finer grained and less recrystallized than that in inset photomicrograph (b), indicating alteration at somewhat lower temperatures. This sample site is less than 50 m below the present-day land surface. Paleostratigraphic reconstruction indicates the maximum



EXPLANATION

- Fragment of vapor-phase coating
- Fragment of calcite coating (dashed where uncertain)
- Calcite subsample
- **5.7** $\delta^{13}C$ of calcite in per mil, PDB (Pee Dee Belemnite)
- *14.5* $\delta^{18}O$ of calcite in per mil, SMOW (Standard Mean Ocean Water)

Figure 7. Photomicrograph of a petrographic section from a secondary mineral coating on a steeply dipping fracture in the Exploratory Studies Facility (ESF) tunnel at about station 52+43. Black square is approximately 2.3 millimeters wide.

burial depth was never more than 125 m (D.C. Buesch, U.S. Geological Survey, oral commun., 2002). Impregnation with blue-dyed epoxy distinguishes primary porosity. In typical hydrothermal systems, such bleaching is commonly accompanied by a change in the whole-rock $\delta^{18}O$ values due to O isotopic exchange between the rock and the altering solution (for example, Criss and Taylor, 1986; and Holt, 2002). The bleached wall rock at ESF station 1+62, however, shows no shift from the $\delta^{18}O$ values of the unaltered wall rock (J.F. Whelan, U.S. Geological Survey, unpub. data, 2003). This indicates that the alteration did not result from interaction with hot, liquid water, but from reaction with water vapor. The O mass balance and, therefore, the capacity for fluid-rock interactions to shift the $\delta^{18}O$ value of the altered rock, is much lower for vapor-rock exchange than for water-rock exchange. The bleached tuff surfaces at locations such as ESF station 1+62 are, therefore, consistent with formation from weak or waning fumarolic systems during the latter stages of tuff cooling and may provide textural and mineralogic analogs for the post-emplacement effects of heated, moist weathering on fracture surfaces in the drift walls.

Examination of the bleached zone at higher magnification (fig. 8 a, b) indicates that this heating coarsened mineral textures and increased porosity. Whether the bleaching also was accompanied by significant changes in tuff chemistry or mineralogy, such as the formation of more easily deformed clay minerals that could facilitate movement along fractures and (or) tuff fragmentation, is not known. Such changes could be determined by X-ray diffractometry or inductively coupled plasma mass spectrometry techniques. Studies of the deposits at ESF station 1+62 could provide useful analogs for the effects of post-waste-emplacement fracture-wall weathering processes on the mineralogy and mechanical strength of fracture surfaces.

Summary

The DDA (BSC, 2003) for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada, describes model simulations of the effects of pre- and post-closure seismicity and waste-induced heating on the emplacement drifts. Based on probabilistic seismic hazard analyses of the intensity and frequency of future seismic events in the region, the DDA concludes that future seismicity will lead to substantial damage to emplacement drifts, particularly those in the lithophysal tuffs, where some simulations predict complete collapse of the drift walls.

Secondary mineral deposits, consisting largely of calcite and silica minerals, are found in some fractures and lithophysal cavities in the UZ, where they have been forming during

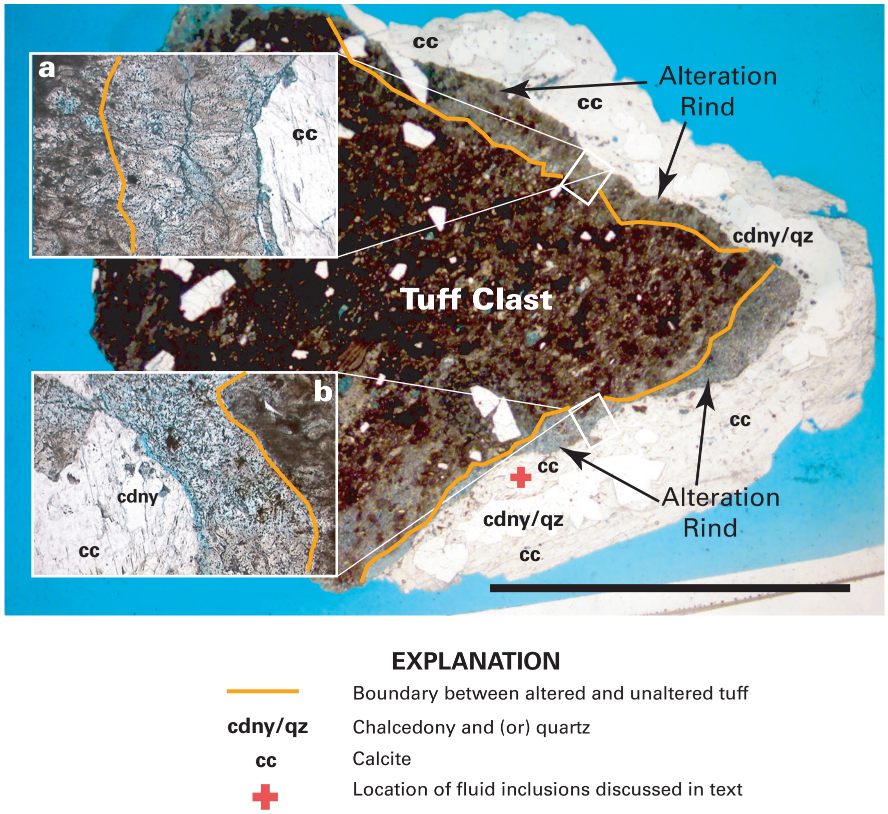


Figure 8. Photomicrograph of a petrographic section of a coating of calcite, chalcedony, and quartz showing early alteration of a near-vertical fracture in the Exploratory Studies Facility (ESF) tunnel at about station 1+62. Alteration texture of inset photomicrograph (a) is finer grained and less recrystallized than that of inset photomicrograph (b). Scale bar is 1 centimeter.

at least the past 10 m.y., and probably since the tuffs cooled to less than 100°C. Depositional temperatures of the secondary minerals ranged to as high as 90°C but were generally from 35 to 60°C during the early stage and parts of the intermediate stage. Late-stage deposition during the past 2 to 4 m.y. appears to have been at or near present-day ambient temperatures of 20 to 25°C. Tuff fragments, likely generated by past seismic activity, are commonly part of the secondary mineral depositional sequences. The secondary mineral deposits, therefore, provide a physical record of the effects of past heating and seismicity on open spaces in the tuffs. Although the secondary mineral coatings have not been systematically examined for evidence of tuff fragmentation, the petrographic thin sections and hand specimens from more than 400 samples collected by the USGS from the ESF and ECRB Cross Drift since 1995 could be used to construct a time-dependent record and spatial distribution map of tuff fragmentation. Preliminary observations indicate that few, if any, tuff fragments were incorporated into mineral coatings during the last 2 to 4 m.y., and there has been little, if any, disturbance of weakly attached coatings and (or) delicate, upright blades of secondary calcite contained in the deposits. Whether or not seismicity-induced tuff fragmentation occurring at centimeter to decimeter scales in the fracture and cavity openings relates directly to failure of tuff walls in the 5.5-m-diameter waste emplacement drifts, the deposits do provide a potential record of the spatial and temporal distribution of tuff fragments in the UZ and an upper limit for ground motion during the late stage of secondary mineral deposition.

The DDA also addresses the alteration of fracture surfaces that will accompany heating to 140 to 160°C in a high-humidity atmosphere and whether it will compromise the contact cohesion between fracture walls (BSC, 2003). Bleaching and alteration at a few of the secondary mineral sites indicate that they were subjected to heated gases at temperatures of at least 90°C. These deposits, therefore, may provide textural and mineralogic analogs for the effects of waste-induced heating on the drift wall rock.

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