Deformation analysis of tuffaceous sediments in the Volcanic Tableland near Bishop, California

Ronald N. McGinnis1,*, Alan P. Morris1, David A. Ferrill1, and Cynthia L. Dinwiddie1

1DEPARTMENT OF EARTH, MATERIAL, AND PLANETARY SCIENCES, GEO SCIENCES AND ENGINEERING DIVISION, SOUTHWEST RESEARCH INSTITUTE, 6220 CULEBRA ROAD, SAN ANTONIO, TEXAS 78238, USA

ABSTRACT

Small-scale brittle faults and fractures that cut bedded tuffaceous sediments of variable textures and grain sizes were studied in a 110-m-long cutbank exposure of poorly consolidated sediments at the southern erosional boundary of the Volcanic Tableland, Owens Valley, California. This study was motivated by the need to evaluate potential length scales for lateral flow in nonwelded bedded tuffs and tuffaceous sediments at Yucca Mountain, Nevada—the site of a potential high-level radioactive waste repository. Small-displacement (<20 cm) faults and fractures are strongly clustered and spatially correlated with larger faults (displacements >20 cm). Vertical fractures are present throughout the exposure, but fracture frequency is generally highest in the vicinity of larger faults. Fault zones are characterized by grain-size reduction and discrete slip surfaces, the number of which increases with increasing displacement. A semiquantitative stress field interpretation, based on tectonic constraints and reconstruction of overburden thicknesses, yields a simple history of burial, deformation, and exhumation under continuous tectonic extension. We interpret the deformation to include shear (faults), hybrid (faults, nonvertical fractures), and tensile (vertical fractures) failure of the tuffaceous sediments under conditions of low overburden stress (<2.5 MPa). The intersecting network of faults and fractures is characterized by grain comminution, cementation, and fracture dilation. These features, in conjunction with stratigraphic layering, likely produce anisotropic permeability, where maximum permeability is parallel to fault and fracture strike.

INTRODUCTION

An understanding of faults and fractures in volcanic and volcaniclastic rocks is of growing worldwide importance for the evaluation of groundwater resources (Winograd, 1971), geothermal energy, contaminant transport, CO2 sequestration (Annumziatellis et al., 2008), and disposal of nuclear waste (Ferrill et al., 1999b; Ofoegbu et al., 2001; Dunne et al., 2003). A number of recent papers have explored various aspects of normal faulting in welded ignimbrites, with emphasis on scaling analyses (Dawers et al., 1993; Dawers and Anders, 1995), segmented fault development (Willemse et al., 1996; Willemse, 1997; Ferrill et al., 1999a), fault-zone deformation mechanisms (Gray et al., 2005), the influence of faults on bulk permeability (Ferrill et al., 1999b), and fault block deformation (Ferrill and Morris, 2001). Relatively little work, however, has examined normal faulting in nonwelded tuffs and tuffaceous sediments (Ferrill et al., 2000; Wilson et al., 2003; Evans and Bradbury, 2004; Dinwiddie et al., 2006).

The specific motivation for this work was to provide the structural geological context for an analog study of an exposure of tuffaceous sediments that was undertaken to help develop an appropriate conceptual model for vadose zone flow in the faulted and fractured Paintbrush nonwelded hydrogeologic unit (PTn) at Yucca Mountain, Nevada. The PTn, which is located stratigraphically above a potential high-level radioactive waste repository at Yucca Mountain, is thought to play an important role in damping pulses of downwardly percolating water in the unsaturated zone between the surface and the potential repository horizon. Natural analog data are of particular interest in the development of a technical basis for evaluating potential length scales for lateral flow within the PTn.

The focus of this study is to improve understanding of deformation characteristics within porous, bedded tephra and tuffaceous sediment and to constrain the effect this type of deformation has on permeability. Here, we examine and characterize, through traditional fault and fracture survey methodologies, the deformation pattern within ash-fall deposits and bedded tuffaceous sediments that are a natural analog to certain bedded tuff units within the PTn at Yucca Mountain. We conclude by presenting a semiquantitative stress analysis that was performed to develop a conceptual model for the deformation history of the tuffaceous sediments at our study site. These sediments are stratigraphically below the Bishop Tuff in northern Owens Valley, California, and they consist of fluvially reworked volcanic material from the Glass Mountain Complex and interbedded ash-fall deposits (Izett et al., 1988). Hereafter, we refer to these tephra and sedimentary deposits as the Crucifix site deposits, using the site name established by Evans and Bradbury (2004). Although the Crucifix site deposits themselves are described as basal Bishop Tuff by Evans and Bradbury (2004), citing work in the region by Wilson and Hildreth (1998), we agree with the interpretation of Izett et al. (1988) based on detailed analysis of this exposure that these deposits are Glass Mountain Complex ash-fall deposits and reworked volcaniclastic sediments.

DEFORMATION IN POROUS MEDIA

Fault-zone processes in porous media have been a major topic of research in recent years.

*Corresponding author e-mail: rmcginnis@swri.org.

Editor’s note: This article is part of a special issue devoted to the GSA Field Forum titled Structure and Neotectonic Evolution of Northern Owens Valley and the Volcanic Tableland, California, convened by David A. Ferrill, Southwest Research Institute, Alan P. Morris, Southwest Research Institute, and Nancye H. Dawers, Tulane University. More papers on this subject will follow in subsequent issues, and these will be collected online at http://lithosphere.gsapubs.org/ (click on Themed Issues).
(Heynekamp et al., 1999; Davatzes and Aydin, 2003; Davatzes et al., 2003; Wilson et al., 2003; Flodin and Aydin, 2004; Odling et al., 2004; Evans and Bradbury, 2004; Shipton and Cowie, 2001; Johansen et al., 2005; Shipton et al., 2005; Sorkhabi and Hasegawa, 2005; van der Zee and Urai, 2005; Dinwiddie et al., 2006). Interest in fault-zone processes is due, in part, to an increased desire to understand the effect that faults and fractures have on the permeability of hydrocarbon reservoirs and aquifers in both saturated and unsaturated conditions. In this paper, we use the term “fault” in reference to an approximately planar discontinuity where displacement parallel to the discontinuity has occurred, and “fracture” is used as a more general term to refer to an approximately planar discontinuity where sense of displacement cannot be clearly discerned. Fractures where displacement is normal to the plane of the fracture are referred to as “extension fractures” or “opening-mode fractures.”

Principal factors that determine fault-zone characteristics within porous lithologies include (1) grain-size distribution, (2) clay content, and (3) degree of compaction, cementation, dissolution, and postdepositional crystallization (diagenesis) (Antonellini and Aydin, 1994; Schultz and Siddharthan, 2005; Aydin et al., 2006). In the case of ash-dominated ignimbrites, increased welding and postdepositional crystallization tend to promote fracturing rather than deformation band (i.e., zones in which grain-size and pore-volume reduction accommodates displacement) formation (Wilson et al., 2003). In poorly lithified porous sandstones, fault-zone width and complexity can be greater in coarse-grained beds than in fine-grained beds (Heynekamp et al., 1999). Fault-zone deformation in porous sandstones (18%–25% porosity) tends to evolve from deformation bands to discrete sheared fractures at higher strains, with later deformation overprinting and reactivating earlier structures (Aydin and Johnson, 1978). The term “deformation band,” however, spans a vast array of features, including those having compactional, dilational, and shear origins (Cuss et al., 2003; Schultz and Siddharthan, 2005; Aydin et al., 2006). Some workers interpreted fault zones in porous sandstones to have originated as joints that later experienced shear deformation (sheared joints; Davatzes and Aydin, 2003). Siliciclastic rocks commonly contain an array of smaller-displacement shear fractures, including discrete faults and deformation bands, clustered around larger-displacement faults (Caine et al., 1996).

Deformation features have different permeability characteristics from their undeformed proclivities. Deformation bands and faults of varying widths and displacements in poorly lithified porous rocks generally have zones of decreased pore size and permeability due to pore collapse from deformation bands (Evans and Bradbury, 2004; Wilson et al., 2003), clay-smear, or cataclastic grain-size reduction (Evans and Bradbury, 2004; Heynekamp et al., 1999). In addition, the clustering of small-scale, permeability-reducing deformation features near larger faults tends to decrease overall permeability in the vicinity of such faults (Knipe et al., 1998; Odling et al., 2004). The overprinting of such deformation features while strain accumulates can lead to changes in permeability characteristics of deformed rock over time (Johansen et al., 2005). For example, exploitation of deformation bands or opening-mode fractures by later slip surfaces will likely increase permeability by creating interconnected fracture porosity (Shipton et al., 2002, 2005).

Previous work on the deposits at the Crucifix site has included characterization of fault geometry, displacements, and kinematics, and microstructural analysis and mineralogic studies of fault-zone deformation (Ferrill et al., 2000; Evans and Bradbury, 2004). Evans and Bradbury (2004) found that fault-zone deformation associated with Crucifix site faults included grain fracturing and comminution (cataclasis), calcite cementation of catalastic material, and fault gouge development (see figs. 13c–f and 16d in Evans and Bradbury [2004] for photomicrographs of these textures).

**GEOLOGIC AND TECTONIC SETTING**

The Crucifix site is located near the town of Bishop, California (Fig. 1A). Owens Valley is bordered by the Sierra Nevada Mountains to the west and the White–Inyo Mountains to the east, and it lies at the western edge of the Basin and Range Province of North America. The valley is a basin that formed by oblique extension during the past 6 Ma (Lueddecke et al., 1998) and is partially filled by volcanic and sedimentary strata (Bateman, 1965; Hollett et al., 1991). The northernmost portion of the valley is characterized by a broad plateau called the Volcanic Tableland (Fig. 1A), which is capped by the Bishop Tuff (Gilbert, 1938). The Volcanic Tableland is a unique area for study because the moderately welded Bishop Tuff is resistant to erosion and has well-preserved fault scars that record the recent extension of Owens Valley (Fig. 1B). This preservation has enabled systematic investigation of its fault systems (Dawers et al., 1993; Dawers and Anders, 1995; Pinter, 1995; Ferrill et al., 1999a, 2000; Evans and Bradbury, 2004; Dinwiddie et al., 2006).

**General Area**

Northern Owens Valley is a broad, tectonic basin bounded by mountain ranges of pre-Cenozoic metamorphic and granitoid rocks (e.g., Hildreth and Mahood, 1986) (Fig. 1A). Pliocene–Pleistocene volcanic activity in Owens Valley was followed by Pleistocene valley glaciation (Gilbert, 1938). Sporadic flooding episodes, in part fed by melting of glaciers, redeposited tuffaceous sediments (e.g., Crucifix site sediments) along the valley floor.

The northernmost part of Owens Valley is covered by the Bishop Tuff, which overlies older morainal and alluvial deposits as well as the Crucifix site sediments. The deposition of the Bishop Tuff is significant for this study because although the Crucifix site sediments are not part of the Bishop Tuff, the original thickness of the overlying tuff sheet produced the maximum lithostatic stress (overburden) experienced by the Crucifix site sediments.

The 0.758 ± 0.0018 Ma (Sarna-Wojcicki et al., 2000) Bishop Tuff consists of nuee ardente–type pyroclastic flows (Gilbert, 1938; Bateman, 1965; Sheridan, 1970; Hildreth and Mahood, 1986; Wilson and Hildreth, 1997, 1998, 2003). The Bishop Tuff exposure, stratigraphically overlying and exposed upslope from the Crucifix site sediments at our study site, consists of a nonwelded tuff that grades upward into a moderately welded tuff. This moderately welded tuff constitutes the present surface of the Volcanic Tableland (Wilson and Hildreth, 1997).

Initial extension of Owens Valley began in the late Miocene and produced westward tilting of the valley floor, which was caused by slip on the Sierra Nevada Mountain frontal fault between 6 and 3 Ma (Lueddecke et al., 1998). At ca. 3 Ma, range-front faulting on the White Mountains frontal fault along the eastern border of Owens Valley marked a switch from westward to eastward tilting of the valley floor (Lueddecke et al., 1998) along the same latitude of the Crucifix site.

Where the Owens River emerges from the Owens River Gorge at the southwest corner of the Volcanic Tableland, it turns sharply eastward and flows across Owens Valley (Fig. 1A), eroding the southern portion of the tableland and forming a naturally exposed east-west profile through the sequence called Chalk Bluff (Fig. 1B). The Crucifix site is located toward the east end of Chalk Bluff where tephra and tuffaceous sediments (i.e., Crucifix site sediments) derived from the Glass Mountain volcanic complex (Metz and Mahood, 1985) are exposed beneath the Bishop Tuff (Fig. 1B; Izett et al., 1988). Small-scale normal faulting and vertical and conjugate fracturing are preserved.
Deformation analysis of tuffaceous sediments in the Volcanic Tableland

RESEARCH

in a cutbank exposure along the Chalk Bluff road at the Crucifix site. The 110-m-long exposure ranges in height from <1 m at each end to ~20 m near its center (coordinates: UTM NAD 27 Zone 11: E = 373761 m, N = 4142025 m). Faults in this exposure have visible displacements of 1 mm to >4 m and include east- and west-dipping faults that intersect and crosscut each other. The crossing conjugate style of faulting observed at the exposure produces horst and graben features (Ferrill et al., 2000).

An understanding of the history of deposition at the Crucifix site is integral to defining the deformation features in the rock. The following section explores the stratigraphic evolution and overburden history (Fig. 2) that led to the deformation that is observed today in the Crucifix site layers. Although not rigorously constrained, the stress history of the Crucifix site can be inferred based on observable data and relatively simple assumptions. After deposition, the Crucifix site layers were buried by the Bishop Tuff 0.76 Ma ago. Since that time, there has been almost continuous exhumation, and ~290 m (Pinter, 1995) of east-west–directed tectonic extension across the ~25-km-wide Owens Valley floor.

Crucifix Site Sediments

The Crucifix site sediments consist of ash-fall deposits and poorly sorted and bedded fluvially reworked ash and pumice interpreted to have originated from the Glass Mountain volcanic complex (Izett et al., 1988). These deposits are characterized by alternating consolidated and poorly consolidated beds that are 20–60 cm thick (Izett et al., 1988). The Glass Mountain volcanic complex was a precursor to the Bishop Tuff eruption and represents the first magma erupted from the Long Valley magma chamber (Metz and Mahood, 1985). The Glass Mountain volcanic complex was composed of high-silica rhyolite lavas that erupted to the northeast of what is now the Long Valley Caldera (Fig. 1A) (Metz and Mahood, 1985), ~40 km northwest of the Crucifix site. The mineralogical and chemical compositions of the Crucifix site sediments are nearly identical to the Bishop Tuff pumice-fall deposits (Izett et al., 1988). Glass Mountain eruptions took place between 2.13 and 0.79 Ma and were never large enough to cause caldera collapse (Metz and Mahood, 1985). The Crucifix site sediments were transported and deposited by debris flows, hyperconcentrated flood flows (Smith, 1986), normal stream flows during the Pleistocene, and primary ash falls. The fluvial deposition was sporadic and highly variable in its flow regime, and the majority of the sediment load was derived from Glass Mountain volcanic complex rocks. Over a period of almost 1.5 Ma, erosion and structural uplift isolated the sediments from this fluvial system as a localized topographic high. This interpretation is evident from the thinning of the Bishop Tuff sequence above the Crucifix site.

Overlying Bishop Tuff

The Bishop Tuff is 48 m thick in the vicinity of the Crucifix site today, and it is composed of a gradational sequence: nonwelded at the base to moderately welded at the top (Wilson and Hildreth, 1997; Evans and Bradbury, 2004) (Fig. 2A). The moderately welded tuff represents the welding maximum for this unit at this location (Wilson and Hildreth, 1997). Pyroclastic (ash-flow tuff) sheets tend to be most densely welded in the middle portion, where
heat is retained longer, and less densely welded at their base and top, where heat is lost rapidly to the substrate below and the atmosphere above (Quane and Russell, 2005; Sheridan and Yang, 2005). Compactional deformation corresponds to the closing of pore space via mechanisms including degassing, mechanical compaction, and welding compaction (Sheridan, 1970). The welding maximum typically occurs between two less welded or nonwelded sections above and below, and consequently, rock density is greatest where compaction and welding are greatest (Ragan and Sheridan, 1972; Quane and Russell, 2005; Sheridan and Yang, 2005). Based on an analog pyroclastic flow (i.e., Matahina ignimbrite; Riehle et al., 1995), the degree of welding observed in the Bishop Tuff near the Crucifix site suggests that the present thickness represents the lower third of the original tuff sheet (Ross and Smith, 1961; Riehle et al., 1995). Using this assumption, the original Bishop Tuff sequence overlying the Crucifix site would have been ~173 m thick and would have graded upward from the moderately welded sequence (welding maximum) at the present topographic surface into nonwelded tuff that has since been removed by erosion (Fig. 2B).

The moderately welded Bishop Tuff exposed at the present-day surface is resistant to weathering and has protected the less resistant sequences of the underlying Bishop Tuff and the Crucifix site sediments from erosion. The nonwelded section that originally lay above the moderately welded sequence was eroded down to the present surface by fluvial and eolian processes and possibly by Pleistocene glaciation (Mayo, 1934). The remaining thickness of the Bishop Tuff directly overlying the Crucifix site exposure was further eroded by the downcutting of the Owens River, which left a small river terrace above the Crucifix site consisting of unconsolidated granite cobbles and gravel derived from the Sierra Nevada Mountains to the west. The original Bishop Tuff sequence (~173 m thick) has, therefore, been removed almost entirely from above the Crucifix site (Fig. 2).

FIELD METHODOLOGY

The geologic methods used to characterize the faults and fractures recorded in the Crucifix site sediments include photography, sketch mapping, mapping on photographs, and measurement of bed and fracture orientations (strike and dip), fault displacements, fault-core thicknesses, and linear fracture frequencies.

Fault Survey

Faults were measured and recorded using a marker bed that spans the width of the horst. All faults that encounter the marker bed have measurable displacements. Faults do not truncate at or within the marker bed, so any bias introduced by surveying within a single bed, which may have different fault spacing or fault properties, does not influence the resulting structural data. Measurements included strike and dip (using the right-hand rule, where the dip direction is clockwise from the recorded azimuth), downdip displacement, and fault-core thickness perpendicular to dip. Slickenslides are not visible on the fault surfaces, so dip-slip movement is assumed based on independent evidence of normal dip-slip from faults in the overlying Bishop Tuff (Dawers et al., 1993). Faults with displacements of ≥1 mm were measured (the criterion for measuring faults this small was that the displacement had to be greater than the aperture). Displacements <1 mm were difficult or impossible to discern in the friable Crucifix site sediments.

To characterize strain at the Crucifix site, the total heave, average extension direction, extension-parallel heave, and total extension were calculated. Downdip displacement measurements were used to calculate the extension-parallel heave for each fault.

Figure 2. (A) Block diagram depicting the conceptual framework of deformation and overburden studied at the Crucifix site. (B) Illustration of the stratigraphic evolution of the Crucifix site.
Fracture Survey

Fractures exposed in two relatively well-consolidated beds were measured within a 15-m-long section in the western part of the exposure (i.e., between 14.92 m and 30.90 m where x = 0 at the western end of the exposure). The upper bed is either a primary ash-fall deposit or a slackwater ash-fall deposit (B. Hill, 2004, personal commun.) with 78 wt% fines (i.e., fines ~0.0625 mm) and geometric mean grain size of 0.15 mm. The lower bed is a reworked pumiceous tephra-fall deposit exhibiting possible development of a paleosol (B. Hill, 2004, personal commun.) with 19 wt% fines and a geometric mean grain size of 0.40 mm. These beds, which were selected for study based on analogy with ash-fall and reworked deposits in the bedded tuffs of the PTn unit at Yucca Mountain, were also sampled in situ for gas permeability.

In this study, a 25-cm-diameter metal ring was centered over each permeability measurement location and some additional localities. Trace length for every visible fracture trace inside the ring was measured, and representative strike and dip orientations were taken. The beds of interest were thinner than 25 cm; therefore, fracture trace lengths above and below these beds were accounted for using this method.

RESULTS

In total, 63 faults and 3196 fractures were measured and documented (Fig. 3A). The orientations of the faults correspond to two conjugate sets (Fig. 3B). Using a Fisher analysis (Fisher et al., 1993), the two sets have an average orientation (strike/dip) of 182/75 (west dipping) and 352/69 (east dipping). The fracture data define three sets of fracture orientations (Fig. 3C). The average orientations (Fisher et al., 1993) for the three sets are 176/90 (vertical), 176/74 (west dipping), and 351/77 (east dipping). Although crosscutting relationships between faults are readily discernible, definitive evidence of crosscutting relationships among fractures is generally lacking. No trends are apparent in the crosscutting of dipping faults; rather, both east-dipping and west-dipping sets appear to offset each other with equal frequency.

Fault-Zone Deformation

Fault zones at the Crucifix site have different geometries depending on the fault displacement and the grain size of the faulted bed (Figs. 4 and 5). We describe the fault-zone deformation in terms of the model presented by Caine et al. (1996), in which fault zones are defined by
(1) fault core, (2) damage zone, and (3) reduced grain size within the fault zone. The centimeter-scale (Figs. 5A and 5B) and subcentimeter-scale displacement faults at the Crucifix site contain distinct slip surfaces with no discernible core or damage zone. The decimeter-scale displacement faults (Fig. 5C) have distinct slip surfaces, but unlike the smaller faults, these have millimeter-scale fault cores and an observed damage zone. Cataclasis and post depositional crystallization are observed along the fracture planes of some of these smaller faults (Fig. 5C). The two meter-scale displacement, horst-bounding faults (Figs. 5D and 5E) have all three components of the Caine et al. (1996) model. More specifically, they each have a measurable central fault core composed of fine-grained gouge and calcite mineralization and a distinct damage zone.

The two meter-scale displacement faults (Figs. 5D and 5E) have cores that are composed of fine-grained comminuted material. Evans and Bradbury (2004) showed that the western bounding fault zone consists of fine ash, tectonized clay, and calcite mineralization. The eastern bounding fault resembles this composition, and both of these faults show bed “drag” geometry, and the fault gouge exhibits clay smear. Fault-core thicknesses vary depending on the grain size of the bed encountered by the fault. Coarse-grained beds (i.e., the gray marker bed in Fig. 5) produce thicker fault cores, whereas fine-grained beds (i.e., bed 1 and bed 2 from the fracture survey) produce noticeably thinner fault cores. Figure 5D and 5E exhibit this trend. In these two images, the wide fault core could be linked to the coarse-grained marker bed between beds 1 and 2, and the thin fault core could be linked to the fine-grained material in bed 1. The bounding faults have cores that are defined by and contain slip surfaces. Most of the associated deformation created by these two faults is observed within the damage zone of the footwall. The damage zone is composed of small, centimeter-scale, conjugate faults and fractures that form a cluster within 1–2 m of the large...
faults. The western bounding fault has a highly deformed footwall that extends 2 m to the east. Across this distance, there are 25 measurable fault traces and abundant nonvertical and vertical fractures. The hanging wall of the western bounding fault has no associated faults and only subvertical fractures that span a few centimeters west of the fault. The western bounding fault is cemented with calcite, veneered with clay, and exhibits fine-grained comminuted gouge combined with glass fragments or pumice clasts, depending upon location. The calcite coatings observed locally along this fault also appear within subsidiary faults in its footwall to the east. The eastern bounding fault has a slightly narrower damage zone (just greater than 1 m in the footwall) with eight identifiable fault traces and numerous nonvertical fractures. The hanging wall of this fault is deformed by five small (<10 cm displacement) faults and nonvertical fractures across a distance of 0.5 m.

Fault Survey

The average strike azimuth for the faults measured at the Crucifix site is 176. Fault dip angles range from 41° to 88° (Fig. 6A), and the average fault dip is 73°. Assuming pure dip-slip displacement, and based on the average strike of the two fault sets, the average extension direction (normal to average fault strike) is 266°, which corresponds to the regional Basin and Range east-west extension direction that is observed in northern Owens Valley. The total fault heave across the 110-m-long exposure is 3.35 m. Correcting fault heave to heave parallel to the average extension direction yields 3.04 m, which represents 3% extension averaged across the entire exposure or 3.8% extension calculated from the first to last fault.

Faulting and the principal zones of displacement are concentrated in two zones at the western and eastern ends of the exposure (Fig. 6). Plots of fault dip, fault-parallel displacement, and fault frequency as functions of position along the transect (Fig. 6) illustrate the distribution of faults and the spatial heterogeneity in the fault system. Fault frequencies were calculated for bin sizes of 2–10 m, and the highest fault frequencies occur at the western end of the exposure (Fig. 6C). A plot of fault-core thickness versus fault displacement data (Fig. 4) shows that the west- and east-dipping faults bounding the horst have the greatest displacements (3.77 and 4.38 m, respectively; Fig. 6B) and relatively thick core zones (0.025 and 0.10 m, respectively). Three faults, however, have much smaller displacements (0.38 m, 0.42 m, and 0.15 m) and yet exhibit comparable core thicknesses (0.03 m, 0.05 m, and 0.02 m). Evans (1990) showed that variation by several orders of magnitude in fault-zone width for a given displacement is common. This might occur because grain size, displacement, and early fault segmentation control fault-zone thickness in these tuffaceous sedimentary rocks. All other faults in the exposure have less than 0.5 m displacement and range in thickness from 0.5 mm to 1 cm.

The heave distribution for the faults at the Crucifix site reveals that a small portion of the total fault population accommodates a large portion of the total heave (20% of the faults account for 92% of the total extension observed in the exposure). Although the majority of the total strain is borne by the two horst-bounding faults, a small component of extensional strain (26%) has been accommodated in the surrounding rock by smaller-displacement faults.

Fracture Survey

A small percentage of vertical fractures exhibited grain or calcite fillings. At some distance from the western bounding fault, the fluvially reworked bed, as observed in thin section, is characterized by dilatant, open fractures and wide, filled fractures containing amorphous silica, iron oxides, or clay. At the Crucifix site, the majority of the fractures, both vertical and subvertical, are opening-mode fractures.

Data from 142 circular sample surveys include measurements of 3196 fractures, 56 faults (63 total faults were measured at the exposure), and 204 sets of strike and dip orientations. Two distinctive fracture patterns are observed—a vertical fracture set and two sets of oppositely dipping steep but nonvertical (conjugate) fractures (Fig. 3C). Vertical fractures predominate in the nonfaulted areas of the exposure, whereas the nonvertical fractures dominate in the highly faulted areas (Figs. 7, 8A, and 8B). Analyses of true
fracture orientations as a function of location in the exposure (Figs. 7, 8A, and 8B) show that vertical fractures are consistently present throughout. The distribution of nonvertical fractures is less consistent; the greatest concentration occurs in a highly faulted section between 15 and 21 m and in a nonfaulted section between 29 and 31 m at the west end of the exposure. Of the fractures mapped at the Crucifix site, 2374 are vertical and 822 are nonvertical. Total fracture length for each set, at each measurement location, is represented by a proportionally scaled line oriented in the dip orientation of the fracture set, as seen in a vertical (dip-parallel) profile (Figs. 8A and 8B). The line diagrams are plotted above (upper bed) and below (lower bed) their location on the photomosaic.

**Stress Analysis and Interpretation of Tectonic History**

There are three possible failure modes within naturally occurring rocks: shear, tensile, and hybrid (e.g., Mandl, 1988). Shear, tensile, and hybrid failure are characterized by the formation of fractures with displacements parallel, perpendicular, and oblique to the fracture surfaces, respectively. Hybrid failure has been interpreted to occur in the transition between shear and tensile failure and requires a tensile minimum principal compressive effective stress ($\sigma_3$). The topic of hybrid failure has been somewhat contentious in the geological literature, and arguments for and against the occurrence of hybrid failure are nicely summarized and critically evaluated by Engelder (1999). However, the most definitive laboratory experiments demonstrating hybrid failure were recently published by Ramsey and Chester (2004). Shear failure surfaces in brittle, less competent rocks have dips in the range of 45° to 75°, whereas hybrid failure surfaces in the same rocks are expected to have dips that range from 75° to 90° (Mandl, 1988; Ferrill and Morris, 2003).

Deformation at the Crucifix site is manifest as vertical fractures and conjugate faults and fractures (Fig. 9). These deformation features are controlled by differential stress, effective minimum principal compressive stress, and the strength characteristics of the rock (Hancock, 1985; Mandl, 1988; Engelder, 1993; Ferrill and Morris, 2003). Figures 10 and 11 depict the interpreted stress history for this exposure.
The stress history of the Crucifix site layers is not rigorously constrained, but we can infer a reasonable and logical stress history based on observations, measured data, and relatively simple assumptions. When the Crucifix site sediments were deposited, vertical stress ($\sigma_1$) would have been negligible (Figs. 10 and 11A). We present a likely sequence of events to illustrate the inferred deformation sequence during the progressive burial and exhumation according to the following time sequence keyed to Figures 10 and 11 and summarized as follows.

At time 1, lithification of the tuffaceous sediments began during burial and as vertical stress increased. Ongoing tectonic extension would have generated a differential stress with $\sigma_3$, oriented approximately east-west and with vertical $\sigma_1$ produced by the lithostatic load of the stratigraphic overburden (Figs. 10 and 11B). Conditions suitable for tensile (mode I) failure are likely to have developed as a response to the low overburden pressure and continued extension. Although stress conditions may have been appropriate for mode I failure, it is possible that the poor grain-to-grain cohesion of the poorly lithified Crucifix site sediments was not appropriate for developing through-going fractures, and no fractures formed at that time. At time 2 (0.76 Ma), the deposition of the Bishop Tuff imposed a sudden increase in lithostatic load on the Crucifix site sediments. Assuming the thickness and density profiles (Wilson and Hildreth, 2003) of the overlying Bishop Tuff and the Crucifix site sediments given in Table 1, the lithostatic stress acting on the tuffaceous sediments would have been between 2.24 and 2.78 MPa (average 2.51 MPa; Table 1; Figs. 10 and 11C). During time period 3, continuous tectonic extension decreased $\sigma_3$ (Figs. 10 and 11). Faults with moderate dips (between 41° and 75°) observed at the Crucifix site are evidence of shear failure, and it is most likely that shear failure conditions were attained shortly after the emplacement of the Bishop Tuff, when decreasing $\sigma_3$ and approximately constant $\sigma_1$ generated sufficient differential stress to reach the failure envelope (Figs. 10 and 11C). Time period 4 represents gradual erosion of the Bishop Tuff, which caused a decrease in $\sigma_3$; continuous tectonic extension and the decrease in lithostatic pressure would have generated a tensile $\sigma_3$ (Figs. 10 and 11D). Conditions for hybrid failure would have occurred, producing nonvertical fractures and faults steeper than 75°. The break

---

**Figure 8.** A photomosaic of the exposure illustrating sample locations and fracture set orientations. Sample locations are marked by black dots and have sample identification numbers. A line diagram is drawn for each sample location. Each black line represents a fracture set that occurs at that location; the line orientation represents dip, and its length represents total fracture length in that fracture set. (Continued on following page).
in slope between time periods 3 and 4 represents the different inferred erosion rates for erosional removal of nonwelded tuff (period 3) versus exhumation of the poorly to moderately welded tuff (period 4). Continued removal of overburden and the subsequent decrease in lithostatic stress, in addition to continuous tectonic extension, would ultimately create conditions under which simple tensile failure (vertical fracturing) could occur (Figs. 10 and 11E). Tensile mode I fractures at the Crucifix site are preserved best where no previous fractures (that could be reactivated) existed.

We interpret that (1) shear fractures formed during conditions of maximum overburden shortly after Bishop Tuff deposition, (2) hybrid fractures formed during the transition between shear and tensile failure, and (3) tensile fractures formed under conditions of low overburden stress (near zero) during erosion of the overburden by the downcutting of the Owens River.

Fault dips at the Crucifix site range between 41° and 88°. Fault-slip surfaces at the Crucifix site with dips in the range of 41° to 75° (~50% of observed faults) are likely, therefore, to be shear mode failure surfaces. The vertical fractures at this location are interpreted to be mode I tensile fractures. The large population of steep, non-vertical, conjugate-style fractures and fault surfaces with dips >75° is interpreted as evidence of hybrid failure, because these steep but non-vertical dips do not match either expected shear or tensile failure angles for the normal faulting regime of the area. Unfortunately, additional evidence for hybrid failure, such as dilational veins, voids, or breccias, was not consistently preserved throughout the exposure due either in part to the advanced state of weathering or to the fact that additional evidence simply does not exist. Therefore, fault and fracture geometries at the Crucifix site suggest that all three failure modes have occurred.

DISCUSSION

In this study, we examine the nature of deformation in sediments that are extremely weak and poorly lithified, in contrast to the many rock types that have been studied by others (Heynekamp et al., 1999; Davatzes and Aydin, 2003; Davatzes et al., 2003; Flodin and Aydin, 2004; Odling et al., 2004; Shipton and Cowie, 2001; Shipton et al., 2005; Johansen et al., 2005). However, many of the features discussed in previous studies are also found in these sediments. At centimeter- and decimeter-scale displacement, some of the faults at the Crucifix site have distinct slip surfaces, and others have characteristics similar to deformation bands described by Wilson et al. (2003) and Heynekamp et al. (1999) in that they exhibit grain-size reduction and cataclasis. These faults commonly show centimeter-scale displacements and form in clusters near the larger-

Figure 8 (continued). (B) Photomosaic and line diagrams for the exposure between 23 and 31 m along the transect.
Deformation analysis of tuffaceous sediments in the Volcanic Tableland

RESEARCH

Deformation analysis of tuffaceous sediments in the Volcanic Tableland

Research

Displacement faults. This association is similar to the damage zones discussed by Caine et al. (1996). The two horst-bounding faults at the Crucifix site have a similar geometry to faults described by Heynekamp et al. (1999). These faults have core zones that contain the main slip surfaces; mixed zones that extend a few centimeters on either side of the fault and that contain irregular slip surfaces and comminuted material; and damage zones that are mostly confined to the footwall side of the faults. The damage zone typically contains a cluster of subsidiary faults and fractures that resemble both deformation bands and simple fractures.

Heynekamp et al. (1999) concluded that coarse-grained sediments experience grain-size reorganization processes (i.e., cataclasis, grain-boundary sliding, and mechanical rotation of grains) during deformation that promotes permeability reduction, strain hardening, and fault growth. In addition, beds with fine-grained sediments go through mechanical rotation and sliding, such as between grains or along discrete slip surfaces or foliation planes, during deformation that promotes decreased permeability, strain softening, and development of narrow fault zones. Similarly, the variation of fault-core width along dip of the two horst-bounding faults at the Crucifix site might be evidence that fault width is a function of the protolith grain size. If that is the case, intrinsic permeability might be decreased by grain comminution and pore collapse in the coarse-grained material, and by clay-smear processes in the fine-grained material.

Two different scenarios may explain faulting and fracturing at the Crucifix site within the context of our interpreted stress history: (1) vertical fractures occurred first and were overprinted by the conjugate faults and fractures during maximum burial and were further overprinted by vertical fractures as the overburden decreased, or (2) conjugate faults and fractures occurred first and were overprinted by vertical fractures as the overburden diminished to its current state. The history of stratal accumulation, erosion, and deformation provides an improved understanding of the in situ stress experienced by these sediments. This approach could also lead to an improved understanding of the evolution of lithologic properties, stress history, and deformation of various units at Yucca Mountain, just as it has for the Crucifix site sediments.

Deformation features within these and other tuffaceous sediments are likely to strongly influence permeability and fluid flow. Deformation at the Crucifix site produced a very high frequency of fractures and small-displacement faults that are localized around

Figure 9. (A) Block diagram illustrating deformation within the 20 m section of outcrop where the circular sample survey was performed. See Figure 2A for context of this block diagram. (B) Block diagram illustrating the deformation characteristics of a highly faulted portion of the exposure. (C) Block diagram illustrating the deformation characteristics near a nonfaulted portion of the exposure. The shaded and ornamental features are as follows: the dark-gray bed is bed 1, the light-gray bed is bed 2, the black lines are faults, the white lines are fractures, and the black dashed horizontal line is the marker bed along which the fault scan-line survey was performed.

Figure 10. Hypothesized stress evolution of the Crucifix site sediments. The illustration shows the circumstances under which shear, tensile, and hybrid failure may have occurred at the Crucifix site. The circled numbers mark points in time at which the stress states shown in Figure 11 are expected to have occurred.
larger-displacement faults. Extension fractures potentially produce more open porosity than in the host material, whereas cataclastic deformation within fault zones produces grain-size and pore-size reduction. The fault frequency observed at the Crucifix site (0.57 faults per meter) is comparable to a PTn data set that was analyzed by Smart (2006). Estimated fault frequencies (the number of faults per meter of tunnel) ranged from 0.22 to 0.33 faults per meter in unsaturated, partially reworked, bedded tuff layers from the PTn (hydrological model layers ptn22, ptn24, and ptn26) exposed in the exploratory studies facility at Yucca Mountain.

The influence of these deformation processes on water movement depends on saturation conditions. Under saturated conditions, open fractures would tend to serve as conduits, and the cataclastic fault-zone material would tend to act as barriers. Under unsaturated conditions, moisture may wick into and be retained in the fine-grained fault zones due to capillary forces, and open extension fractures may act as barriers because of moisture retention in the smaller pores of adjacent host rock. Ponded infiltration tracer tests in the nonwelded Bishop Tuff, which has a high capillary wicking potential, showed that a highly deformed section of rock with vertical and subvertical fractures enhanced vertical flow by laterally constraining flow paths (Fedors et al., 2001). Under these locally saturated conditions, the fractures that are partially cemented with caliche-like cement did not act as conduits, but rather as boundaries that defined preferential flow blocks. Deformation features like those analyzed at the Crucifix site influence potential fluid pathways and produce permeability anisotropy in the faulted and fractured strata in different ways depending on the saturation conditions.

**CONCLUSIONS**

After deposition, the tuffaceous sediments at the Crucifix site underwent a period of shear, hybrid, and up to two episodes of tensile failure that produced the observed pattern of conjugate faults and fractures and vertical fractures. Two oppositely dipping normal faults in the exposure form a horst. These two faults account for 75% of the total fault extension in the exposure. Stress analysis based on overburden estimation suggests that low differential stress (on the order of 2.5 MPa) with a near-zero minimum principal stress produced the observed deformation.

The Crucifix site exposure contains some of the least lithified tuffaceous sediments for which rock failure has been studied. The level of consolidation, however, does not prevent these rocks from preserving deformation features that

---

**TABLE 1. SUMMARY OF THICKNESS, DENSITY, AND STRESS RANGES FOR A SECTION OF THE BISHOP TUFF LOCATED NEAR THE CRUCIFIX SITE**

<table>
<thead>
<tr>
<th></th>
<th>Thickness (m)</th>
<th>Density (kg/m³)</th>
<th>Lithostatic stress (MPa) (g/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bishop Tuff</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonwelded (upper)</td>
<td>34</td>
<td>1250</td>
<td>1320</td>
</tr>
<tr>
<td>Poorly welded (upper)</td>
<td>53</td>
<td>1170</td>
<td>1330</td>
</tr>
<tr>
<td>Moderately welded</td>
<td>43</td>
<td>1160</td>
<td>1320</td>
</tr>
<tr>
<td>Poorly welded (lower)</td>
<td>26</td>
<td>1170</td>
<td>1330</td>
</tr>
<tr>
<td>Nonwelded (lower)</td>
<td>17</td>
<td>1250</td>
<td>1320</td>
</tr>
<tr>
<td>Glass Mountain sediments at Crucifix site</td>
<td>20</td>
<td>1100</td>
<td>1300</td>
</tr>
<tr>
<td>Sum</td>
<td>193</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Thickness and density values were taken from Wilson and Hildreth (2003). Lithostatic stress was calculated by multiplying the thickness (t), free-fall acceleration constant (g), and the density (d).
are very similar to those observed in studies of high-porosity sandstones, other poorly lithified siliciclastic rocks, nonwelded tuffs, and other tuffaceous sediments. These features include (1) cataclastic shear deformation and extension fracturing, (2) variations in fault-zone thickness and geometry controlled by lithology, (3) clusters of small-displacement faults and fractures that form near larger-displacement faults, and (4) the overprinting of different failure modes and deformation mechanisms.

Deformation features influence the intrinsic permeability of the system. Fault-zone deformation commonly involves grain-size and pore-volume reduction resulting in reduced permeability. Under unsaturated conditions, the smaller mean pore size produces an increased capillary (wicking) effect in addition to reduced permeability. A fault system such as this would influence fluid flow both vertically and laterally. Vertical fluid movement would be focused downstream, and lateral fluid movement would be restricted horizontally by faults that behave as flow barriers. Influences such as these would potentially enhance fluid flow in a direction parallel to the intersection line of conjugate faults. The fault system will influence groundwater movement under both saturated and unsaturated conditions. This influence may differ, however, since open faults and fractures can act as conduits under saturated conditions and barriers under unsaturated conditions.

ACKNOWLEDGMENTS

This paper was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the United States Nuclear Regulatory Commission (NRC) under contract no. NRC-02-02-012. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of High-Level Waste Repository Safety. This paper is an independent product of CNWRA and does not necessarily reflect the views or regulatory position of NRC. The authors thank Britt Hill and Good- luck Ofegbue for providing technical assistance, and Britt Hill, Gary Walter, Wes Patrick, Kevin Smart, Zoe Shipton, and Jim Evans for their technical reviews.

REFERENCES CITED


MANUSCRIPT RECEIVED 21 JANUARY 2009
MANUSCRIPT ACCEPTED 29 APRIL 2009
Printed in the USA

304 www.gsapubs.org | Volume 1 | Number 5 | LITHOSPHERE

Downloaded from https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/1/5/291/3044260/1941-4264-1-5-291.pdf by guest