CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

SUBJECT: Institute of Geophysics and Planetary Physics (IGPP) Workshop on Fluid Flow and Transport through Faulted Ignimbrites and Other Porous Media (06002.01.131)

DATE/PLACE: September 7–10, 2003; Santa Fe, New Mexico

AUTHORS: C. Dinwiddie

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AUTHOR: C. Dinwiddie

PERSONS PRESENT:

Cynthia L. Dinwiddie, of the Center for Nuclear Waste Regulatory Analyses (CNWRA), attended the Institute of Geophysics and Planetary Physics workshop on fluid flow and transport through faulted ignimbrites and other porous media. CNWRA consultants Mary Beth Gray (Bucknell University, Lewisburg, Pennsylvania) and Kelly Keighley Bradbury (Utah State University, Logan, Utah) were also in attendance. Workshop conveners were Claudia Lewis (Los Alamos National Laboratory, Los Alamos, New Mexico), Laurel Goodwin (New Mexico Tech, Socorro, New Mexico), and Jennifer Wilson (New Mexico Tech, Socorro, New Mexico). A list of other attendees is appended to this report.

BACKGROUND AND PURPOSE OF TRIP:

The issues focused on during this workshop were highly relevant to ongoing NRC and CNWRA evaluations of the structure and hydrology of the Paintbrush Tuff at Yucca Mountain, Nevada, and the workshop venue provided an excellent opportunity to receive feedback on CNWRA work on the Bishop Tuff as a natural analog for the Paintbrush Tuff. The nonwelded Paintbrush Tuff, which overlies the repository horizon, is assumed to spatially and temporally dampen episodic percolation moving through the moderately welded Tiva Canyon Tuff. Numerical model simulations (CRWMS M&O, 2000) show that a porous, permeable nonwelded tuff (e.g., the Paintbrush) may attenuate rapid, transient fracture flow from the Tiva Canyon Tuff; hence, a steady-state assumption is often made for unsaturated flow through the fractured tuffs of Yucca Mountain. Recent work at the Bishop Tuff natural analog has focused on the potential that faults, fractures, and fault zone deformation have to disrupt lithologic barrier-induced lateral diversion of flow. An understanding of this potential is important for NRC oversight of DOE activities because the updated unsaturated zone flow model for any license application may take credit for significant lateral diversion in certain Paintbrush Tuff units, therefore reducing the estimated amount of water that reaches the repository horizon.

SUMMARY OF ACTIVITIES:

The first full day of the workshop was comprised of a hands-on field trip through selected areas of the Pajarito Plateau, Bandelier Tuff, New Mexico. The purpose of the field trip was to examine evidence of petrophysical controls (porosity, degree of cementation, grain mineralogy, etc.) on deformation behavior, and to encourage discussion of how spatial variations in petrophysical controls impact vadose zone and groundwater fluid flow in the vicinity of faults.

On the second and third days of the workshop, oral presentations and poster sessions were followed by panel-led discussions. Topics included deformation processes, flow and transport through faulted porous media, fault zone diagenesis, and future directions in the study of fault-fluid interactions in granular porous media.

During the final session of the workshop, attendees discussed ways to foster multi-disciplinary communication on the following topics of relevance:

- Rock mechanics
- Testing models of fluid-rock interaction related to fault failure
- Remote sensing
- Spatial/temporal variation in a fault zone
- Biogeochemical processes in fault zones
- Fluid pressure variations in fault/protolith systems (i.e., coupled hydromechanical systems)
- Controls on fault zone deformation processes
- Dating fault-related features
- Episodicity in the geologic record
- Diagenesis as a record of paleo-flow/pore volumes
- Characterization of heterogeneity
- Construction of fault zone conceptual models (e.g., hydrological and paleoseismological)
- Construction of fault zone predictive tools
- Identification of appropriate model boundary conditions
- Multiphase transport
- Rivulet or fingering flow
- Indicators of flow through faults
- Consequences of flow through faults
- Use of isotopic tracers for tracing fluid source/flow path
- Long-term vs. short-term flow pathways
- Identification of "research faults" that are representative of particular fault classes
- Monitoring present-day hydrologic activity of faults in areas of societal interest (e.g., Yucca Mountain)
- Identifying the ideal toolbox for monitoring/instrumenting faults

Ideas set forth for fostering communication necessary to advance the science:

- Production of a fault/fluid interaction book/monograph on the current state of the science
- Future meetings at two-year intervals; Meeting sponsorship sought from the following organizations: Institute of Geophysics and Planetary Physics (IGPP), Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI), American Association of Petroleum Geologists (AAPG), Geological Society of America (GSA–particularly for field conference funding), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA–particularly for a remote sensing workshop on the identification of fault/fluid interactions)
- Special sessions at the American Geophysical Union (AGU) or Geological Society of America (GSA) annual meetings
- Chapman and or Penrose conferences

SUMMARY OF PERTINENT POINTS:

Faults can function as either barriers or as conduits. The fault core experiences the greatest amount of deformation; it is finer-grained than the surrounding material, and thus tends to be a relatively low permeability element. The surrounding fault damage zone experiences less deformation; it is characterized by fractures, and is thus a relatively high permeability element.

There are three possible modes of deformation that are dependent upon the mechanical strength of a geologic unit: i) the weakest materials deform by particulate flow; ii) moderately strong units deform through formation of deformation bands; and iii) the strongest materials deform by fracturing. Moderate-strength materials exhibit small grain contact areas, high porosity, and generally deform through formation of deformation bands, while high strength materials have large grain contact areas, low porosity, and generally deform by fracturing. Deformation bands are generally low permeability elements, while fractures are generally high permeability elements.

In contrast to the notion that deformation bands are generally low permeability elements, Marjorie Chan (University of Utah) spoke about eolian deformation bands that evidently illustrate the propensity for formation of preferential flow paths. The eolian Navajo sandstone was originally red in color due to the presence of hematite grain coatings. Reducing brines mobilized the iron and bleached the sandstone white. These iron-rich waters traveled through preferred pathways until the iron was finally reprecipitated as iron concretions (Moqui Balls or Moqui Marbles) along deformation bands. While the physical evidence appears convincing, the results of this study are controversial within the scientific community because they countermand the current understanding, which is that deformation zones function as flow barriers. The dilatency of a deformation band is very rapidly concluded, so it is difficult to understand how enough pore volumes could flow through to successfully bleach iron and later reprecipitate it in the form of concretions. Organics may play a role in local reprecipitation of iron, and it was suggested that one could extract organic material from the deformation bands in order to search for phospholipids that could indicate a biogenic source of redox reactions.

The degree to which an ignimbrite weathers is a function of material strength. The first stop on the field trip provided an excellent opportunity to observe a nonwelded, glassy tuff unit of impressive strength. Nonwelded tuff may be strengthened enough to become indurated by vapor-phase alteration, oxidation, and case-hardening processes.

The trip report appendix contains the field-trip literature, the workshop schedule of presentations, and attendee contact information. Field-trip photographs, workshop presentations and posters may soon be found on the workshop website at http://www.ees.nmt.edu/Geol/Faults/Faultsflow/ igppworkshop.html.

CONCLUSIONS:

This workshop venue provided an excellent opportunity for receiving positive peer community feedback on CNWRA work at the Bishop Tuff natural analog for the Paintbrush unit at Yucca Mountain, as well as for soliciting additional ideas from the scientific community regarding our field observations. Information gathered on the state of the science at this workshop reinforces our position that significant lateral flow over long distances within the Paintbrush Tuff is unlikely. Small faults distributed throughout the nonwelded Paintbrush Tuff will likely disrupt any laterally flowing fluid, while the surrounding fault damage zones will tend to enhance the vertical flow of water.

PROBLEMS ENCOUNTERED:

None.

PENDING ACTIONS:

None.

RECOMMENDATIONS:

None.

REFERENCE:

CRWMS M&O. "Unsaturated Zone Flow and Transport Model PMR." TDR–NBS–HS–000002. Rev. 00. Las Vegas, Nevada: CRWMS M&O. 2000.

SIGNATURES:

Cynthia L. Dinwiddie — Date 10/16/03
Cynthia L. Dinwiddie
Research Engineer

CONCURRENCE:

E. C. P. — Date 10/17/2003
English C. Pearcy
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Budhi Sagar
Technical Director

IGPP-Sponsored Workshop on Fluid Flow and Transport through Faulted Ignimbrites and other Porous Media

Workshop Schedule

Sunday, Sept. 7, 2003

5:45 PM *Dinner for early arrivals*

• Posters can be put up between Sunday night and Tuesday morning. All posters will be up for the entire workshop.

7:00 PM *Reception*

Monday, Sept. 8, 2003

7:30-8:15 AM *Breakfast*

8:30 AM Leave Ghost Ranch for Field Trip *(box lunches will be provided)*

Field Trip Topic: **Deformation Bands in Nonwelded Ignimbrites: Petrophysical Controls on Fault-Zone Deformation and Evidence of Preferential Vadose-Zone Fluid Flow** Jennifer Wilson (New Mexico Tech, NMT), Laurel Goodwin (NMT), and Claudia Lewis (Los Alamos National Lab, LANL)

Presentations on Field Trip:

Analysis of intrinsic and extrinsic controls on fault-zone deformation of poorly lithified materials, and implications for hydrologic studies Laurel Goodwin (NMT), Jennifer Wilson (NMT), and Geoffrey Rawling (New Mexico Bureau of Geology and Mineral Resources, NMBGMR)

• **Deformation-band faults in sand are conduits for vadose-zone fluid flow in arid environments** John Sigda (NMBGMR) and John Wilson (NMT)

5:15 PM Return to Ghost Ranch

5:45 PM *Banquet*

Tuesday, Sept. 9, 2003

7:30-8:15 AM *Breakfast*

MORNING SESSION: **Deformation Processes**

Oral presentations:

8:20 AM Introductory remarks

8:30 AM Keynote: **Mechanical deformation and permeability evolution of porous media** Teng-Fong Wong (SUNY, Stonybrook)

9:10 AM **A comparative analysis of fault zone architectures in welded tuff at Yucca Mountain, NV, with implications for paleohydrology** Mary Beth Gray (Bucknell University)

9:30 AM **Internal architecture, permeability structure, and hydrologic significance of contrasting fault-zone types** Geoffrey Rawling (NMBGMR), Laurel Goodwin (NMT), and John Wilson (NMT)

Poster Session I:

9:50 AM Authors introduce posters (4 minutes each)

10:15 AM Break to view/discuss posters, *Coffee Break*

Preliminary investigation of microscale fault textures associated with aseismic creep and coseismic rupture in active fault zones S.M. Cashman (Humboldt State University), J.N. Baldwin (Wm. Lettis and Associates), and K.V. Cashman (Univ. of Oregon, Eugene)

Cataclasis and particulate flow in faulted, poorly lithified sediments Geoffrey Rawling (NMBGMR) and Laurel Goodwin (NMT)

Fracture-based deformation in a non-welded ignimbrite of the Bandelier Tuff Claudia Lewis (LANL), Alexis Lavine (LANL), Jennifer Wilson (NMT), and Danielle Katcher (LANL)

Deformation of non-welded Bishop Tuff: processes and impact on fluid flow in the unsaturated zone Kelly Keighley Bradbury (Utah State University) and James Evans (Utah State University)

Characteristics of brittle distributed deformation zones in Precambrian crystalline rocks of the central Colorado Front Range Jonathan Caine (U.S. Geological Survey)

11:30 AM Reconvene for discussion, led by panel including Teng Fong Wong, Mary Beth Gray, Geoffrey Rawling
Potential topics for discussion: 1) Differences between deformation behavior of granular media and fully lithified rock. 2) Extrinsic (e.g., confining pressure, strain rate) versus intrinsic (e.g., porosity, cementation) controls on fault-zone deformation processes: can we predict fault-zone architecture and permeability structure? 3) Effective integration of experimental deformation studies and field research. 4) Large versus small-displacement faults; how do fault zones evolve and what are the implications of that evolution for hydrologic modeling?

12:00 PM *Lunch*

AFTERNOON SESSION: **Flow and Transport through Faulted Porous Media**

Oral presentations:

1:30 PM Keynote: **Hydrologic impact of faults in granular media** John Wilson (NMT)

2:10 PM **In situ measurement of nonwelded tuff permeability where heterogeneities are induced by fault zone deformation, Bishop Tuff, Bishop, California** Cynthia L. Dinwiddie(Center for Nuclear Waste Regulatory Analyses, CNWRA), Randall W. Fedors (CNWRA), David A. Ferrill (CNWRA), Kelly K. Bradbury (Utah State University)

2:30 PM **Simulated Impact of Faults on CO_2 Injection for Oil Recovery and CO_2 Sequestration** Craig Forster (Univ. of Utah, Salt Lake City)

Poster Session II:

2:50 PM Authors introduce posters (4 minutes each)

3:10 PM Break to view/discuss posters, *Coffee Break*

Fault zone properties and potential for compartmentalization of groundwater aquifers in poorly lithified, Rio Grande rift-related, Santa Fe Group sediments, New Mexico Jonathan Saul Caine (U.S.G.S.), Scott M. Minor (U.S.G.S), V. J. S. Grauch (U.S.G.S.), and Mark R. Hudson (U.S.G.S.)

Interpretation of pneumatic field tests in unsaturated fractured rocks at the Apache Leap Research Site, Arizona Velimir V. Vesselinov (LANL)

The Role of Diffusive Mass Transfer on Nonreactive Solute Transport in Fractured Volcanic Tuff Timothy J. Callahan (LANL), Paul W. Reimus (LANL), and Robert S. Bowman (NMT)

Investigation of the influence of faults on groundwater movement and contaminant migration in the Pahute Mesa/Oasis Valley flow model domain, Nevada Andrew Wolfsberg (LANL), Ed Kwicklis (LANL), Dave Broxton (LANL), Dave Vaniman (LANL), Wendy Soll (LANL), and Carl Gable (LANL)

4:15 PM Reconvene for discussion, led by panel including John Wilson, Cynthia Dinwiddie, Craig Forster
Potential topics for discussion: 1) Effective incorporation of qualitative geologic data into quantitative hydrologic models. 2) Constraints on saturated and unsaturated fault-zone permeability structure. 3) Upscaling issues.

5:15 PM Break

5:45 PM *Dinner*

Wednesday, Sept. 10, 2003

7:30-8:15 AM *Breakfast*

<u>MORNING SESSION: **Fault-Zone Diagenesis**</u>

<u>Oral Presentations:</u>

8:30 AM Keynote: **Fault zone diagenesis – what we see and what we don't in examples from Southern California** James Boles (Univ. California, Santa Barbara)

9:10 AM **Chemical bleaching: An indicator for fluid flow in sandstone deformation bands** Marjorie A. Chan (Univ. of Utah, Salt Lake City), W. T. Parry (Univ. of Utah), and Brenda Beitler (Univ. of Utah)

9:30 AM • **A hydrologic perspective on fault-zone diagenesis** John Sigda (NMBGMR)

<u>Poster Session III</u>

9:50 AM Authors introduce posters (4 minutes each)

10:05 AM Break to view/discuss posters, *Coffee Break*

Petrophysical, geochemical, and inferred hydrologic characteristics of deformation bands in nonwelded ignimbrites of Los Alamos, NM, and Busted Butte, NV Jennifer Wilson (NMT), Laurel Goodwin (NMT), and Claudia Lewis (LANL)

[• **Fault-zone diagenesis as a record of fluid-rock interaction along the Pen Branch fault zone, southern Appalachians** Allen Dennis (Univ. of South Carolina, Aiken)]

An analysis of the role of fluids in fracture initiation and propagation using direct simulation of the coupled fluid-solid system David Boutt (NMT)

11:00 PM Reconvene for discussion, led by panel including James Boles, Marjorie Chan, and John Sigda
Potential topics for discussion: 1) More effective utilization of fault-zone diagenesis as a record of fluid-rock interactions and paleohydrology. 2) The impact of diagenetic minerals on reactive flow and transport. 3) Using diagenetic history and microstructural analysis to determine relative timing of deformation and lithification.

12:00 PM *Lunch*

AFTERNOON SESSION

1:30 PM Discussion: Future Directions in Study of Fluid-Fault Interactions in Granular Porous Media. Among other topics, we will discuss approaches to:

- Investigating physical controls on fault-zone deformation
- Quantifying the hydrologic properties of structures produced by different deformation mechanisms
- Developing methods to more effectively model flow and transport through faulted porous media, particularly incorporating diagenetic changes within and outside fault zones.

Coffee and cookies will be available during the discussion

2:30 PM **Wrap-up and summary of key results of meeting** Laurel Goodwin, Claudia Lewis, and Jennifer Wilson

3:00 PM **End of formal meeting.** Participants are encouraged to continue discussion or explore Santa Fe!

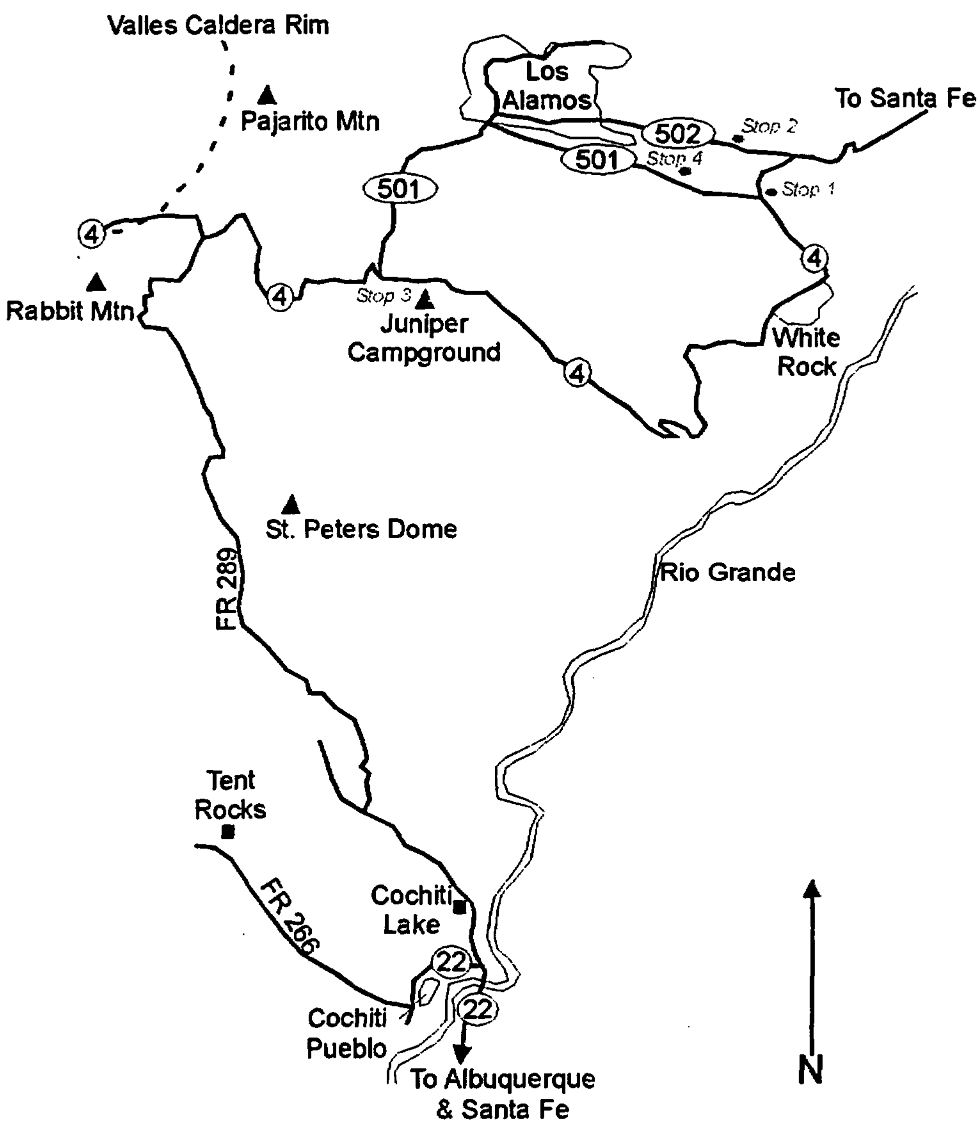
Deformation Bands in Nonwelded Ignimbrites: Petrophysical Controls on Fault- Zone Deformation and Evidence of Preferential Vadose-Zone Fluid Flow

A Field Trip Through Selected Areas of the Pajarito Plateau

IGPP-Sponsored Workshop on Fluid Flow and Transport through Faulted Ignimbrites and other Porous Media, September 8, 2003

Field Trip Leaders: Jennifer Wilson (New Mexico Tech), Laurel Goodwin (New Mexico Tech), and Claudia Lewis (Los Alamos National Lab)

Guest Speakers: John Sigda (New Mexico Bureau of Geology and Mineral Resources) and Emily Shultz (Los Alamos National Lab)



Introduction

Studies of fault impacts on fluid flow generally involve the incorporation of existing conceptual models of fault-zone architecture and permeability (e.g., Caine et al., 1996) into flow models. Such conceptual models are primarily based on studies of rocks faulted at depths greater than 3 km and subsequently exhumed (e.g., Chester and Logan, 1986). In general, structures within these faults were not studied to determine their impact on fluid flow; they were examined to understand the impact of fluids on the mechanics of earthquakes and faulting. At these crustal levels (within the seismogenic zone), rocks are fully saturated and both temperature and pressure are elevated with respect to surface conditions. Rocks that have been buried and deformed at depths of several kilometers or more include both crystalline and fully lithified sedimentary and volcanic rock; therefore, both intrinsic properties (e.g., porosity) and extrinsic parameters (such as confining pressure) are different from those of granular materials deformed at near-surface conditions.

Our work indicates that mechanisms of deformation at depths of less than a kilometer in fault zones in poorly lithified sediment are distinct from those in crystalline and low porosity sedimentary rock, resulting in different structures and a different impact on permeability (Heynekamp et al., 1999; Rawling and Goodwin, 2003). Large-displacement faults in sediment have a significantly greater effect on regional, cross-fault groundwater flow than structures of similar size in low porosity rock (Rawling et al., 2001). This work suggests that if we want to understand the impact of near-surface fault-zone deformation of granular media on fluid flow, we need to characterize the fault-zone deformation and permeability structure of near-surface faults in these materials.

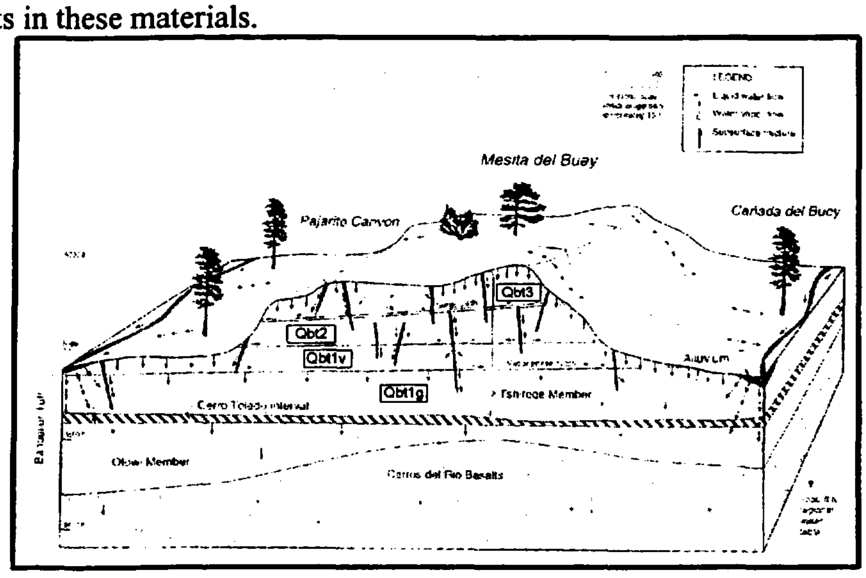


Figure 1. Conceptual model of vadose-zone fluid flow beneath the Pajarito Plateau. From Turin and Rosenberg (1996).

The Bandelier Tuff, exposed in and near Los Alamos, NM, provides an ideal natural laboratory for study of faults in granular media because the ages of the deformed materials, depth of faulting, and location of the water table are well constrained (Fig. 1), which has allowed us to evaluate petrophysical (e.g., composition, porosity, etc.) controls on deformation behavior (Wilson et al., in press). The purpose of this field trip is to view and discuss the evidence for such controls on deformation, along with the evidence for fault-zone impacts on fluid flow in the vadose zone. This trip is intended to serve as a springboard for discussion of the broader issues of near-surface faulting in granular media in general, and the impact of faults in granular media on both vadose-zone and groundwater flow.

Detailed Schedule and Commentary

8:30-9:15am *Travel from Ghost Ranch in Santa Fe to Tsankawi Ruins, Bandelier National Monument.*

In addition to spectacular scenery, the road onto the Pajarito Plateau offers an excellent stratigraphic section through the Bandelier Tuff and underlying units. The tuff includes the 1.6 Ma Otowi Member and the 1.2 Ma Tshirege Member (Smith and Bailey, 1966; Izett and Obradovich, 1994; Fig. 2), which comprise material erupted from the Toledo and Valles Calderas to the west (Fig. 3). The spatial distribution and variations in stratigraphic thickness of individual units of the Bandelier Tuff reflect factors such as the energy of the eruptions, distance from the caldera, paleotopography, and prevailing wind patterns during eruptive events (e.g., Heiken et al., 1990). As we drive towards Los Alamos, Claudia will draw your attention to outcrops of the Plio-Pleistocene volcanic and volcaniclastic deposits of the Puye Formation and the Pliocene basalts of the Cerros del Rio volcanic field, on which the Bandelier Tuff was deposited. She will also point out the weathering characteristics of different units within the physically heterogeneous tuff. We will return to these stratigraphic reference points throughout the day as we investigate the mechanical significance of the factors that dictate resistance to weathering, color, and texture of individual units.

9:15-10:00am **Stop 1:** *Tsankawi Ruins, Bandelier National Monument. Introduction and restroom break.*

As mentioned earlier, we expect variations in the character of fault-zone deformation to result from variations in both extrinsic (e.g., confining pressure, temperature, pore fluid pressure, strain rate, etc.) and intrinsic (e.g., porosity, degree of cementation, mineralogy of grains, etc.) parameters (e.g., Wong et al., 1997). A key goal of this field trip is to discuss which intrinsic characteristics of ignimbrite deposits influence their deformation behavior, and how variations in the resulting structures impact fluid flow.

Ignimbrites (or pyroclastic flows) are produced by explosive volcanic eruptions. One emplacement model involves gravitational collapse of an eruptive column of gas, molten rock, crystals, and entrained debris (Wright, 1979; Sparks and Wilson, 1976). The momentum of this collapse is maintained as the resulting gas-charged flow (ignimbrite) moves away from the caldera at high speeds. The physical characteristics of the material deposited from a given ignimbrite depends on a variety of factors, including melt composition and the thickness and temperature of the flow at the time and place of deposition (which varies with distance from the caldera).

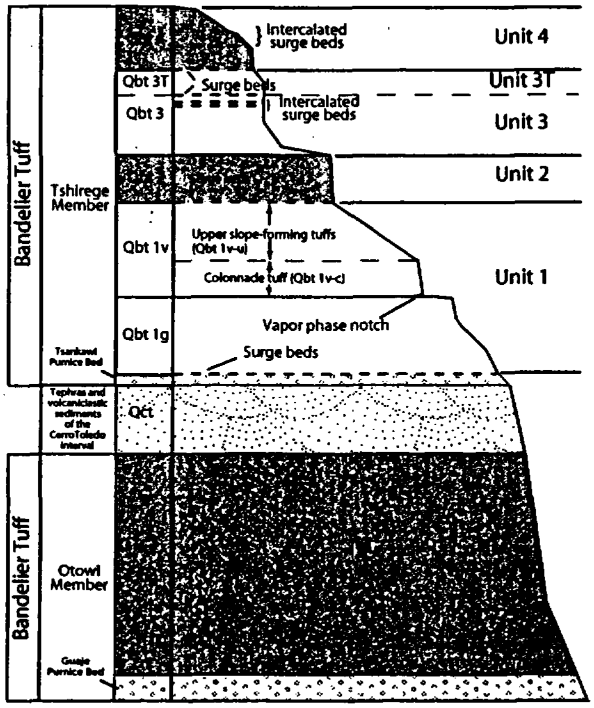


Figure 2. Generalized stratigraphy of the Bandelier Tuff (modified from Broxton and Reneau, 1995).

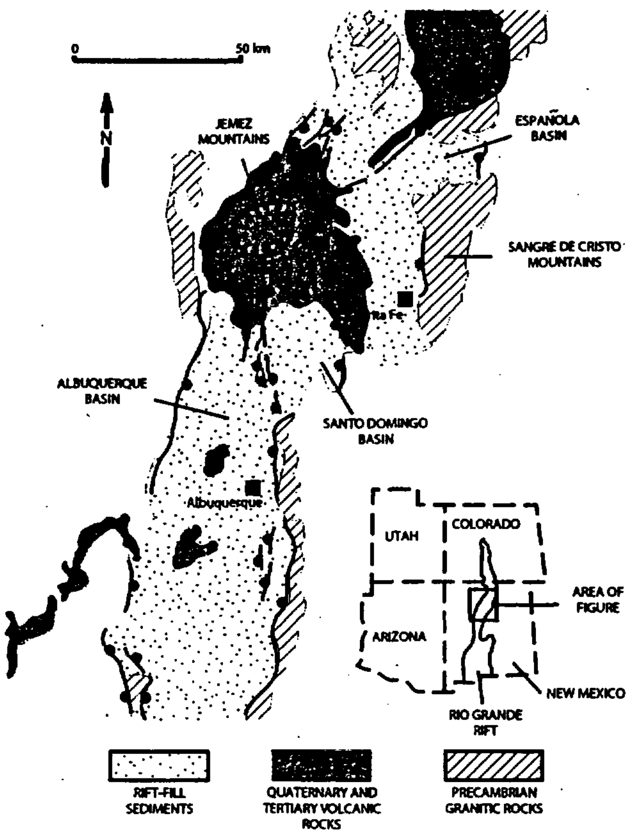


Figure 3. Map of the Rio Grande rift in northern New Mexico. Major fault systems are shown schematically (ball on downthrown side). VC is the Valles-Toledo caldera complex, the source of the Bandelier Tuff (modified from Gardner and Goff, 1984).

Ignimbrite deposits are, not surprisingly, heterogenous with respect to a variety of petrophysical characteristics. They comprise variable amounts of glass in the form of pumice and ash, phenocrysts, and lithic fragments. Both the Tshirege and Otowi members of the Bandelier Tuff are dominated by silicic ash with subordinate pumice, quartz and alkali feldspar phenocrysts (generally 10-25 vol%), and lithic fragments (Broxton and Reneau, 1995; Fig. 4a). It is important to note that other ignimbrites may, for example, be more enriched in pumice or lithic fragments. The relative amounts of these different components can influence both mechanical and hydrologic characteristics.

Where ignimbrites are sufficiently hot, grains may be fused together and compacted by the weight of the overlying deposit. This process of welding destroys some porosity and produces a pronounced horizontal anisotropy in the rock (Fig. 4b). In addition, crystallization of minerals from vapor trapped in pores and/or devitrification of glass in ash and pumice (Fig. 4c) may occur shortly after deposition (Stimac et al., 1996). All of these processes can affect the mechanical (Moon, 1993) and hydrologic (e.g., Winograd, 1971) properties of the rock. For example, welded ignimbrites are mechanically stronger than non-welded ignimbrites.

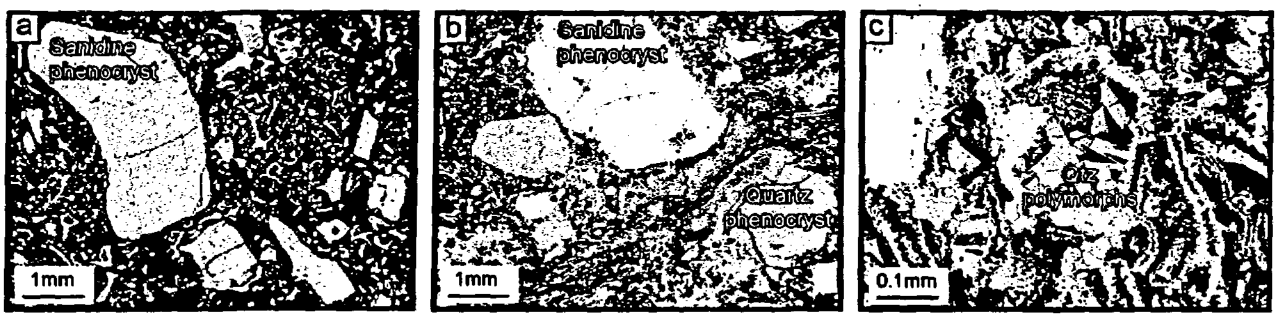


Figure 4. Back-scattered electron images of Bandelier Tuff. (a) Non-welded, glassy unit 1g. (b) Welded, crystallized unit 2. (c) Non-welded, crystallized unit 3.

The Otowi Member is a single, non-welded, glassy cooling unit (Fig. 5). The Tshirege Member comprises a sequence of cooling units, which vary in degree of welding and postdepositional crystallization. The outcrops we will visit here show that non-welded glassy units are highly friable, and generally weather to form slopes of unconsolidated material, in many cases covered with colluvium. Welded units and strongly crystallized or oxidized portions of non-welded units are resistant to weathering and therefore generally form cliffs. The latter units are typically characterized by cooling joints that, as can be seen on a topographic bench we will stand on, form networks of fractures connected in a polygonal pattern. Previous work has demonstrated that these fractures may be reactivated as faults (Rogers et al., 1996).

We have identified a mechanical stratigraphy within the Bandelier Tuff based on the distribution of structures of different kinds (i.e., fractures versus deformation bands; Wilson et al., in press; Fig. 5). The mechanical stratigraphy is controlled by variations in degree of welding, postdepositional crystallization, and alteration, and therefore largely corresponds to cooling units identified by previous workers (e.g., Broxton and Reneau, 1995). In general, hydrologic units correspond to mechanical units. We will investigate some of these different structures at the next stop.

10:05-10:20am *Travel from Tsankawi Ruins to Camp Hamilton Trail*

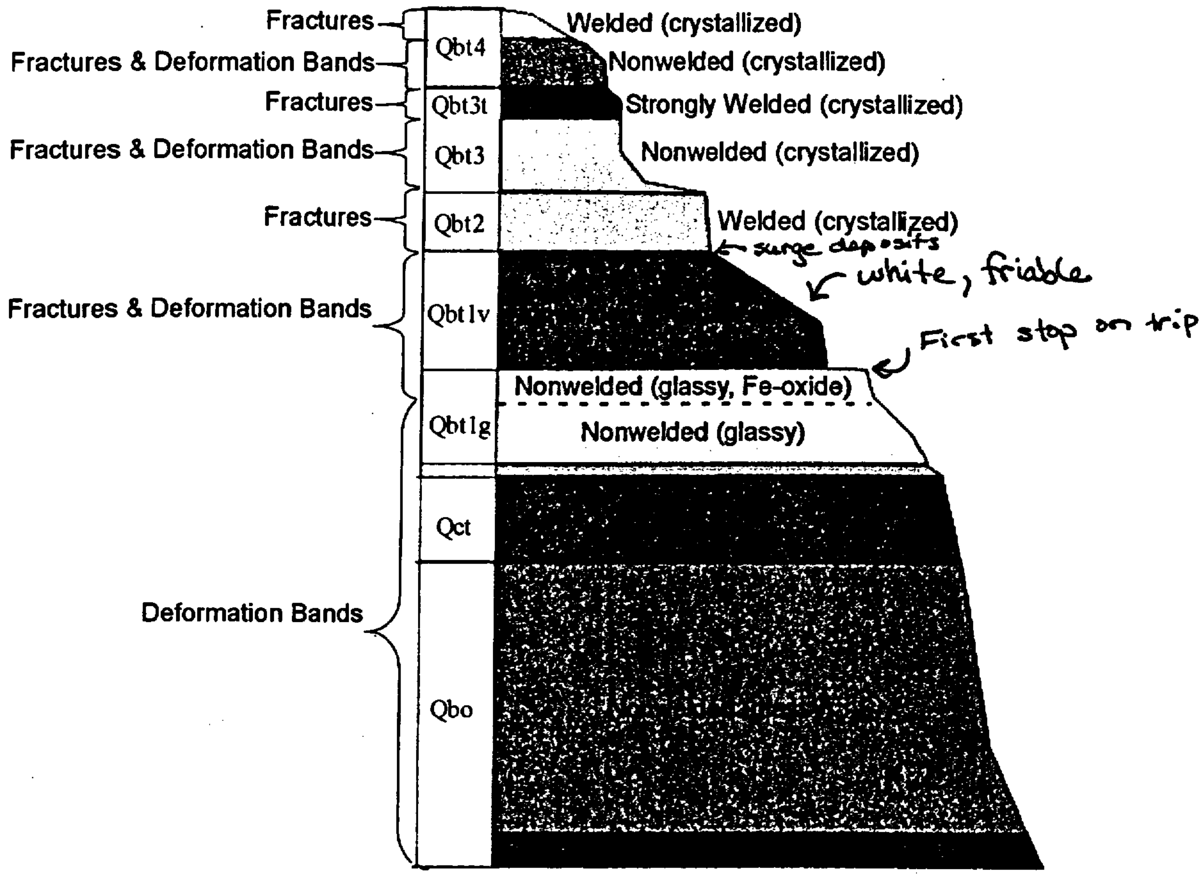


Figure 5. Mechanical and petrophysical characterization of the Bandelier Tuff.

10:20am-12:20pm **Stop 2:** *Tectonic setting and petrophysical controls on fault-zone deformation of ignimibrites.*

The Valles Caldera is situated at the intersection between the Rio Grande rift and the Jemez lineament (believed to reflect a crustal discontinuity developed during the Mazatzal orogeny, ca. 1.65 Ga; e.g., Aldrich, 1986; Fig. 2), on the eastern margin of the Colorado Plateau. Volcanism is broadly associated with development of the rift. However, for reasons not well understood, most eruptive activity since about 5 Ma has taken place along the Jemez lineament, oblique to the rift axis (e.g., Baldridge et al., 1987). The Pajarito fault zone, the main westernmost bounding fault system of the Española Basin of the Rio Grande rift, cuts the Bandelier Tuff to our west. To the east, syntectonic sediments of the Santa Fe Group fill the basin between us and the rift-flanking Sangre de Cristo Mts (e.g., Cavazza, 1989; Ingersoll et al., 1990). In this dynamic rift environment, faulting, volcanism, deposition of sediments, and processes of soil development are broadly synchronous. In our area of interest, the Pajarito fault zone formed prior to deposition of the Bandelier Tuff (e.g., Gardner and Goff, 1984) and has been active as recently as 1.4-2.2 ka (McCalpin, 1998). The fault zone is characterized largely by normal displacement, although strike-slip movement is locally significant (e.g., Gardner et al., in press).

Our research has focused on small-displacement faults, presumably associated with the Pajarito fault system, for several reasons. With displacements of millimeters to a couple of meters, these faults juxtapose similar geomaterials. By concentrating on small-displacement faults, we can directly relate fault-zone character to rock type, and address the hydrologic impacts of deformation and fluid-rock interaction without the complicating effects of juxtaposing strata with different permeabilities. In addition, small-displacement faults are far more numerous than large-displacement faults in this area (e.g., Carter and Winter, 1995) and in a variety of settings important for energy and groundwater resources. Understanding two-phase (e.g., hydrocarbon/water or water/air) flow through small-displacement faults in granular media is therefore critical to addressing a variety of problems of societal interest, including contaminant transport through thick desert vadose zones and production from faulted petroleum reservoirs.

The potential impact of faults on fluid flow and transport through thick vadose zones in ignimbrite sequences depends in part on the nature of fault-zone deformation. Both fractures and deformation bands have been found at Los Alamos, NM, and Busted Butte, NV. The primary controls on mode of failure are grain-contact area and strength, which are directly related to degree of welding and crystallization and inversely proportional to porosity (Wilson et al., in press). Low porosity welded units deform by transgranular fracture; high porosity, glassy, non-welded units deform by cataclasis within shear deformation bands (cf. Aydin and Johnson, 1978;). Moderately high porosity, non-welded units that have undergone devitrification or vapor-phase crystallization form either shear deformation bands or fractures, depending on local variations in the degree and nature of crystallization.

The Camp Hamilton Trail provides the opportunity to hike through a slice of Bandelier Tuff stratigraphy into the underlying Cerro Toledo interval. In this interval, we will investigate deformation-band faults, including two that can be seen to extend into zones of fractures in the overlying, mechanically stronger strata (Fig. 6). To accomplish as much as possible, we will

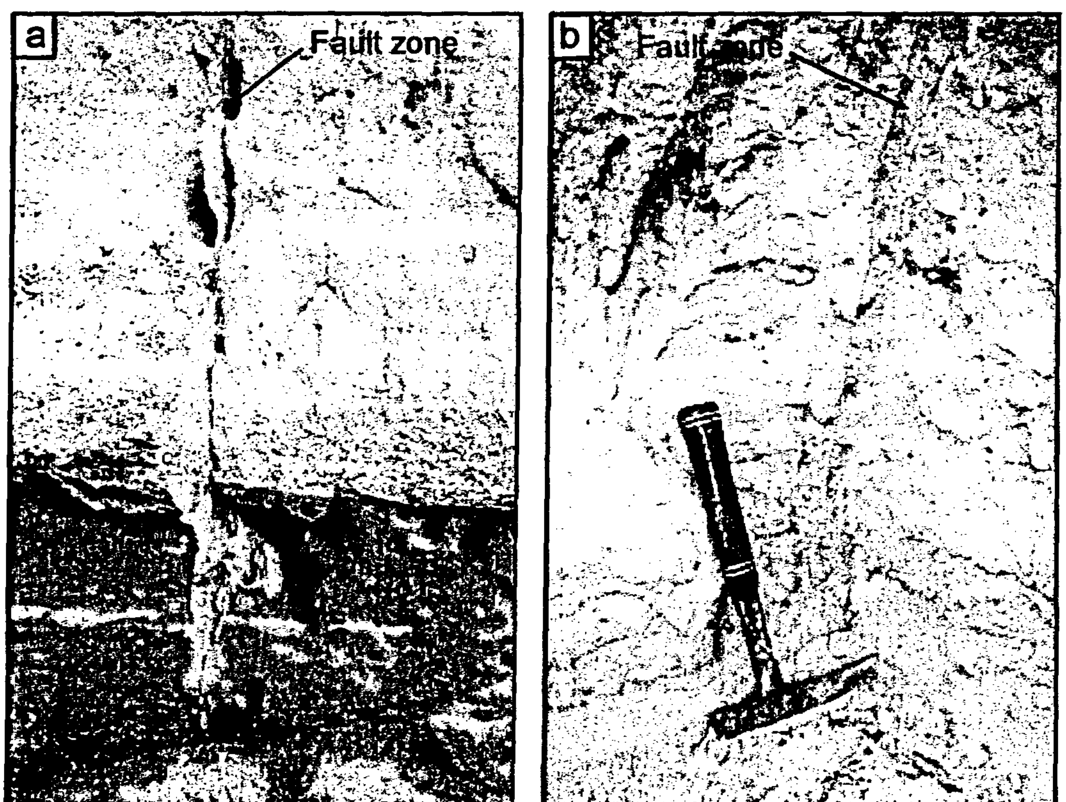


Figure 6. Deformation-band faults in the Cerro Toledo interval, exposed along the Camp Hamilton trail.

break into three groups at the base of the escarpment. One group will go with Laurel to look at one of the above-mentioned fault that changes structural character as it traverses different stratigraphic units. A second group will join Jennifer to look at the internal structure of a deformation-band fault zone exposed in cross section. A third will go with Claudia to look at a deformation band fault in a thin, pumice-rich layer. The groups will be shuffled between these closely spaced exposures until all participants have seen each of the outcrops. (Interestingly, these are dominantly strike-slip faults.)

12:15-12:30pm *Travel from Camp Hamilton Trail through LANL to Juniper Campground*

12:30-1:30pm *Lunch and restroom break at Juniper Campground*

1:30-1:50pm **Stop 3:** *The Pajarito fault escarpment*

The Pajarito fault forms the active western boundary of the Rio Grande rift near Los Alamos, where it strikes north to northeast along the western margin of Los Alamos National Laboratory. Detailed field studies of 7 km of the 40-km-long Pajarito fault show that the geometry of the fault varies appreciably along-strike (McCalpin, 1997; Gardner et al., 1999; Schultz et al., 2003). The fault is expressed at the surface as a large normal fault, a faulted monocline, and a distributed zone of deformation with significant east-side-down normal displacement of the 1.2 Myr-old Tshirege Member of the Bandelier Tuff. Emily Schultz will share key details of her map of the Pajarito fault escarpment with the group. These details should be kept in mind over the next few days as we consider the impact of faults and fault zones of different size on flow and transport above and below the water table. Such considerations demand an understanding of fault patterns at a variety of scales. Following Emily's presentation, we will take a brief trip up the escarpment before returning to an evaluation of outcrop- and finer-scale structures.

2:00-2:30pm *Travel from Juniper Campground, up Pajarito fault escarpment, back down to LANSCE site, LANL*

2:30-4:30pm **Stop 4:** *LANSCE(Los Alamos Neutron Science Center)*

Site 1:

As mentioned earlier, welded ignimbrites fail solely through fracturing in this near-surface environment. Glassy, non-welded ignimbrites form only deformation bands. Nonwelded, crystallized ignimbrites fail through the formation of both fractures and deformation bands. We believe this generally reflects spatial variations in the magnitude and nature (mineralogy, crystal structure) of postdepositional crystallization. This site affords us the opportunity to consider protolith characteristics and fracture distributions in a nonwelded, crystallized ignimbrite. We will also investigate the detailed structure of an unusual, composite fault zone that includes both zones of deformation bands and fractures (Fig. 7). We will divide participants into two groups to address both topics, and rotate groups between areas on the extensive outcrop.

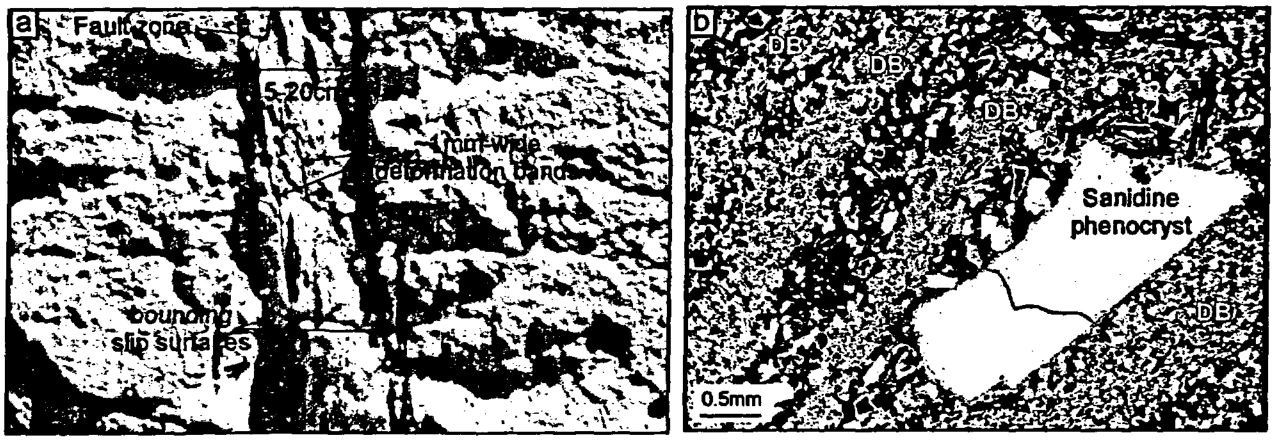


Figure 7. Outcrop (a) and back-scattered electron image (b) of a deformation-band (db) fault in nonwelded, crystallized Qbt3, located along the beamline roadcut at LANSCE.

Site 2:

Grain- and pore-size reduction in shear deformation bands commonly produces indurated, tabular zones of clay-sized fault material in the Bandelier Tuff (Wilson et al., in press). Many of these bands are locally rich in smectite and/or cemented by carbonate. Preferential wetting of deformation bands is inferred to promote alteration and cementation. We therefore interpret variably altered fault-zone material as evidence of preferential fluid flow in the vadose zone, which we infer to result from enhanced unsaturated permeability due to pore-size reduction in deformation bands. This interpretation relies on the results of previous work conducted by John Sigda and John Wilson on deformation-band fault zones in poorly lithified sand (Sigda and Wilson, 2003). At this site, we will divide participants into two groups. The first will look at evidence of diagenetic/pedogenic processes in both deformation bands and fractures. The second will join John Sigda for a brief overview of his work demonstrating that deformation band faults in sand are conduits for vadose-zone fluid flow in arid environments.

4:30-5:15pm *Travel from LANL to Ghost Ranch in Santa Fe*

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