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Deformation bands in nonwelded ignimbrites: Petrophysical controls on fault-zone deformation and evidence of preferential fluid flow

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ABSTRACT

The impact of faults on fluid flow and transport through thick vadose zones depends in part on the nature of fault-zone deformation. Both fractures and deformation bands occur in ignimbrite sequences at Los Alamos, New Mexico, and Busted Butte, Nevada. 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. Low-porosity welded units deform by transgranular fracture; high-porosity, glassy, nonwelded units deform by cataclasis within deformation bands. Moderately high porosity, nonwelded units that have undergone devitrification and/or vapor-phase crystallization form either deformation bands or fractures, depending on local variations in the degree and nature of crystallization. Grain- and pore-size reduction in deformation bands commonly produces indurated, tabular zones of clay-sized fault material. 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.

INTRODUCTION

Faults can affect fluid flow through the juxtaposition of hydrologically distinct lithologic units and by changes in fault-zone permeability through deformation, alteration, and cementation (e.g., Knipe, 1993; Caine et al., 1996; Rawling et al., 2001). Where fault displacement is less than bed thickness, flow is affected only by structural and diagenetic modification of the fault zone. Fault-zone structures have been described in geologic materials ranging in strength from crystalline rock (e.g., Chester and Logan, 1986; Reches and Lockner, 1994) to high-porosity sandstones (e.g., Aydin and Johnson, 1978; Antonellini and Aydin, 1994) and poorly lithified sediments (e.g., Mozley and Goodwin, 1995; Cashman and Cashman, 2000). These studies demonstrate that fractures are the fundamental fault-zone structure in crystalline and low-porosity sedimentary rock, whereas deformation bands are dominant in high-porosity sandstones and poorly lithified sands. Deformation bands are narrow zones in which grain-size reduction through cataclasis, grain-boundary sliding, and pore collapse accommodate millimeter- to centimeter-scale displacements. In contrast to fractures, deformation bands reduce porosity and saturated permeability with respect to the protolith (e.g., Antonellini and Aydin, 1994; Sigda et al., 1999). Under unsaturated conditions, permeability is a function of water content and pore size. In semiarid to arid climates, where small pores retain more water effectively than large pores, low-porosity deformation bands can be up to six orders of magnitude more permeable than their protolith (Sigda and Wilson, 2003).

These field-based studies suggest that the primary controls on mode of failure of a given rock include the petrophysical properties of the protolith. Deformation experiments have isolated specific properties, such as grain size and porosity, that affect whether a rock fails by fracture or cataclastic flow (e.g., Wong et al., 1997). These studies also emphasize the importance of extrinsic variables, such as effective pressure.

Ignimbrites are spatially heterogeneous pyroclastic flow deposits consisting of poorly sorted assemblages of phenocrysts, pumice, and lithic clasts in a glassy matrix. Ignimbrite units show a range in degree of welding (compaction and fusion of matrix glass and pumice) and postdepositional crystallization (e.g., devitrification and vapor-phase crystallization, by which secondary minerals replace glass and grow in pore spaces, respectively). These processes are dependent on such factors as eruption temperature and melt composition (Smith and Bailey, 1966). Welding decreases porosity and increases grain-contact area and strength: compaction enlarges contact area, and fusion of contacts increases their strength. This increase in area and strength of grain contacts provides a rigid framework through which fractures may propagate, thereby increasing the rock's mechanical strength (e.g., Moon, 1993). Postdepositional crystallization also reduces porosity and can increase grain-contact area and strength where interlocking crystals replace glass and grow across grain margins.

In this paper we document deformation bands in ash-dominated ignimbrites near Los Alamos, New Mexico, and at Busted Butte, Nevada. Deformation bands have previously been described only in high-porosity sandstone and poorly lithified sand. Because their impact on fluid flow is quite different from that of fractures, we have evaluated what controls whether a given ignimbrite unit fails by fracture or by cataclasis within a deformation band. Confining pressure is low in these near-surface deposits, and variations in extrinsic properties within the study areas are negligible; this allows us to isolate the effect of petrophysical properties on deformation. This is the first systematic study of physical controls on fault-zone structure in a natural laboratory setting. We have found that welded units fail by fracture, whereas failure by cataclasis within deformation bands occurs only in nonwelded units; thus, degree of welding is the primary control on mode of failure. Spatially variable postdepositional crystallization exerts a secondary control on mode of failure, inferred from the observation that nonwelded, crystallized ignimbrites exhibit both shear fractures and deformation bands.

Widespread alteration and cementation of deformation bands provide evidence that they have served as preferential fluid flow paths in the vadose zone. Pore-size reduction may therefore enhance the unsaturated permeability of deformation bands in ignimbrites. Although rarely mapped because of their size, small-displacement faults like these are common in tectonically active areas (e.g., Carter and Winter, 1995), and their character and spatial distribution are important to consider when evaluating fault-zone impacts on fluid flow (cf. Sigda et al., 1999).

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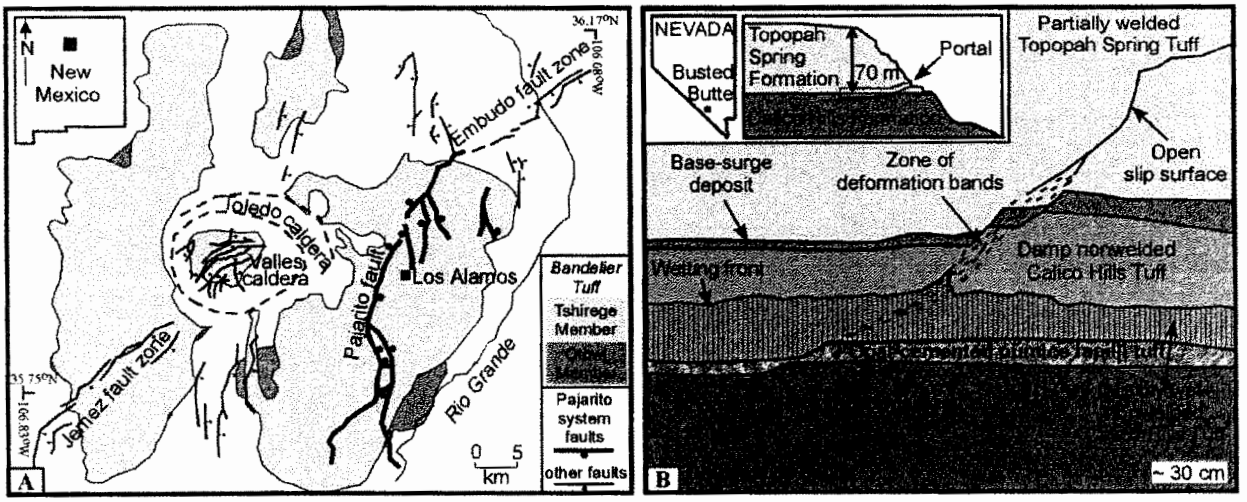

Figure 1. A: Location and simplified structure map of Jemez Mountains, modified from Aldrich (1986), Heiken et al. (1990), and Purtymun (1995). Study area includes Bandelier Tuff east of Pajarito fault system. B: Normal-fault exposure in Busted Butte Unsaturated Zone Transport Test facility final mine-back face. Inset gives location, schematic cross section of stratigraphy, and location of portal that leads to face illustrated in larger diagram. Fault-zone character changes from slip surface in partially welded Topopah Spring Tuff to zone of deformation bands in nonwelded Calico Hills Tuff. Striped pattern denotes extent of preferential wetting.

STUDY SITES

Bandelier Tuff, Los Alamos, New Mexico

The Bandelier Tuff of northern New Mexico includes the 1.6 Ma Otowi Member and the 1.2 Ma Tshirege Member (Fig. 1A; Smith and Bailey, 1966; Izett and Obradovich, 1994). Both are dominated by silicic ash; they have subordinate amounts of pumice, phenocrysts of quartz and sanidine, and lithic clasts (Broxton and Reneau, 1995). The Otowi Member is a single, nonwelded, glassy ignimbrite unit. The Tshirege Member comprises a sequence of ignimbrite units that vary in degree of welding and postdepositional crystallization.

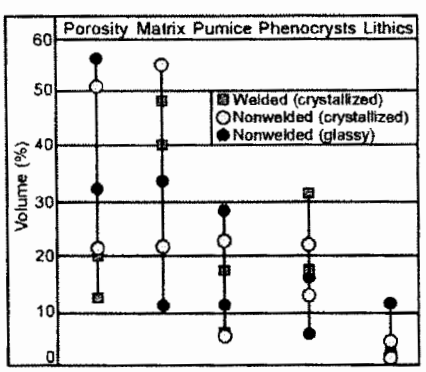

Figure 2. Porosity and grain types in undeformed Bandelier and Calico Hills Tuffs. Porosities determined from pixel counts of backscattered electron images; relative abundance of grain types determined from point counts on petrographic microscope. Matrix includes intact glass shards, ash, and crushed pumice (glassy or crystallized). Data from three samples of welded units, six samples of crystallized, nonwelded units, and six samples of glassy, nonwelded units.

In the vicinity of Los Alamos, the Bandelier Tuff is cut by the 41-km-long, rift-related, Pajarito normal-fault system, comprising four large fault traces, each dipping steeply west or east and striking approximately north (Fig. 1A). Displacement is typically dip slip, as much as 180 m on the Pajarito fault, with local evidence of strike slip (Carter and Gardner, 1995). Numerous small-displacement faults (millimeter- to meter-scale throw) are the focus of this study.

Busted Butte, Nevada

Normal faults also cut ash-dominated ignimbrite strata in Busted Butte, Nevada (Fig. 1B). These 13 Ma silicic ignimbrites include the Topopah Spring Member of the Paintbrush Tuff and the Calico Hills Formation (Broxton et al., 1987), which are stratigraphically correlative and mineralogically similar to unsaturated units between the potential high-level nuclear waste repository at Yucca Mountain and the underlying water table (Turin et al., 2002). Major faults associated with Basin and Range extension dip steeply, strike approximately north, and juxtapose ignimbrite units by hundreds of meters of dip slip and left-lateral strike slip. Smaller displacement faults occur between these major faults; we studied one of these at the Busted Butte Unsaturated Zone Transport Test facility (Turin et al., 2002). Tracer migration in the test facility was monitored and analyzed at mine-back faces, the last of which exposed the fault on which we focused. Tracers did not reach the portion of the fault investigated.

METHODS

In addition to study of the fault already mentioned, field characterization of more than 100 small-displacement fault zones was conducted in the Bandelier Tuff. Petrographic analysis of oriented samples of faults and corresponding protolith was followed by backscattered electron (BSE) imaging and quantitative chemical analysis of clays and alteration phases, performed on a Cameca SX-100 electron microprobe operated at 15 keV and 20 nA beam current. Pixel counts of black (porosity) versus gray (grains) in 100 BSE images per protolith thin section (3 sections per sample) were used to quantify porosity.

Bulk mineral contents of fault-zone material and corresponding protolith were determined by quantitative X-ray diffraction (XRD) analysis using the FULLPAT QXRD method (Chipera and Bish, 2001). Diffraction patterns were obtained on a Siemens D500 X-ray powder diffractometer using Cu$K\alpha$ radiation, incident- and diffracted-beam Soller slits, and a Kevex Si(Li) solid-state detector from 2° to 70° 2θ, using 0.02° steps, and counting for at least 2 s per step.

FAULT-ZONE STRUCTURES IN IGNIMBRITES

Fractures Versus Deformation Bands

The ignimbrites display spatially variable welding, porosity, postdepositional crystallization and matrix ash, pumice, phenocryst, and lithic clast content (Fig. 2). Poorly lithified, nonwelded units (pumice aspect ratio < 6:1) have high porosity and exhibit variable amounts of crystallization (0–24 wt% cristobalite ± tridymite). Welded units (pumice aspect ratio > 6:1) are crystallized, have higher phenocryst and ash contents per unit volume, and have considerably lower porosity (Fig. 2).

Fractures are the only fault-zone structures

Figure 3. A: Deformation bands in nonwelded, crystallized Bandelier Tuff. B: Backscattered electron image of deformation band (DB) in sample from A. Note reduction in both porosity (black) and size of phenocrysts (Ph), crystallized glass shards (G), and pumice fragments (P) in deformation band.

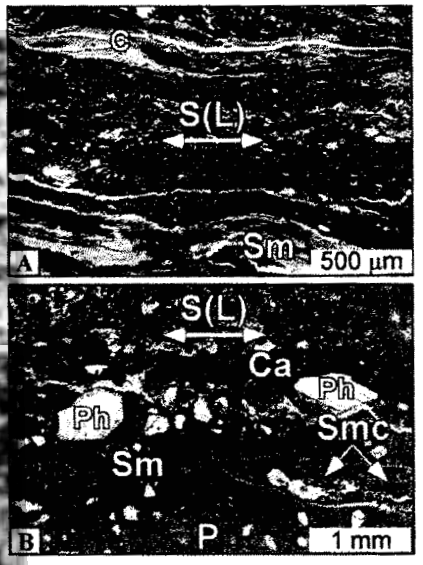

Figure 4. A: Plane-light photomicrograph of clay-rich deformation-band fault zone. Foliated smectite (Sm) and bands of smectite with ignimbrite fragments (S) are parallel to fault plane (arrow). Elongate clasts define slip-parallel lineation (L). Desiccation cracks (C) in pure smectite bands formed during sample preparation. B: Scanned thin-section image of deformation-band fault zone with foliation (S) defined by bands of smectite (e.g., Sm) and carbonate (Ca, black) containing clasts of smectite (Smc), crushed phenocrysts, glass, and pumice. Some phenocrysts (Ph) were rotated into alignment with slip direction (L) without crushing. Boundary between deformation band and protolith (P) is irregular.

observed in welded units. In contrast, deformation bands are the only structures found in high-porosity, glassy, nonwelded units. Moderately high porosity units that are not welded but have undergone postdepositional crystallization exhibit both deformation bands and fractures, commonly in the same outcrop. In the latter cases, deformation bands and fractures have similar orientations, but rarely intersect, instead occurring in spatially distinct zones. In one outcrop, a fracture crosscuts a zone of deformation bands.

Deformation-band fault zones are 0.1–15 cm wide and vary in complexity from a single deformation band to a zone of anastomosing bands (Fig. 3). At the microscopic scale, they exhibit diffuse, nonplanar boundaries, which locally weave around large phenocrysts and lithic clasts. Deformation bands exhibit lower porosity and smaller pore and grain sizes than protolith. Grain crushing has destroyed the walls of pumice vesicles, connecting previously isolated pore space even though porosity is reduced. Elongate grains are typically aligned and pores are elongate parallel to aligned grains, recording dip, oblique, or strike slip for a given fault, consistent with the variety of sense of slip indicators on larger faults in the area (Carter and Gardner, 1995). Pore throat size was reduced by this grain alignment, which likely decreased the tortuosity of flow pathways. Silt-sized grains are common; large grains are locally preserved. XRD analyses confirm petrographic observations that fine-grained fault material consists mostly of ignimbrite fragments with variable amounts of alteration minerals and/or cement (see Data Repository[1]).

Alteration and Mineralization

More than two-thirds of the deformation bands contain some smectite (1.4–93%) and/or carbonate cement (2.8–42.4%). These minerals line or fill pore space and, in faults reactivated subsequent to alteration and/or cementation, help define a compositional-banding foliation with cataclastic ignimbrite material (Fig. 4).

Clay-rich deformation bands (0.1–3 cm wide) are characterized by bands of foliated smectite that anastomose around fragments of ash, pumice, phenocrysts, and lithic clasts (Fig. 4A). Multiple episodes of deformation and clay enrichment are evidenced by crosscutting relationships between clay-rich bands that contain variable amounts of cataclastic ignimbrite fragments and have slightly different chemical compositions.

Some clay-rich deformation bands are also variably cemented by microcrystalline carbonate. Grain-size reduction and fault-parallel alignment of elongate grains and pores are evident in these 0.5–5-cm-wide fault zones. Episodic fault movement, alteration, and cementation are recorded by aligned pores and bands of carbonate that typically contain clasts of both ignimbrite and smectite and anastomose around foliated smectite bands (Fig. 4B).

Mode of Failure Transition

A range in structures was observed in a single, continuous fault zone at Busted Butte (Fig. 1B). The 0.5–10-cm-wide fault zone shows 10 cm of apparent throw. Where it cuts partially welded Topopah Spring Tuff, the fault zone consists of fractures. In the nonwelded base-surge deposit of the Topopah Spring Tuff and the nonwelded Calico Hills Tuff, it consists of deformation bands, indicating that mode of failure is directly dependent on degree of welding of the protolith. Part of the Calico Hills Tuff is preferentially wet with water injected into an opal-cemented lapilli tuff layer during the Unsaturated Zone Transport Test (Turin et al., 2002; Fig. 1B). The wetting front extends farther into the fault zone than into the surrounding material, suggesting that it has different hydrologic properties than the protolith.

DISCUSSION

Controls on Fault-Zone Structure in Ignimbrites

Deformation bands are observed in glassy, nonwelded units in the Bandelier Tuff and at Busted Butte; fractures are observed in welded units. Welding increases the mechanical strength of the rock (Moon, 1993) by decreasing porosity and increasing grain-contact area and strength. We therefore infer that welding influences mode of failure.

Postdepositional crystallization can decrease porosity and increase grain-contact area and strength in nonwelded units via occlusion of porosity and production of a fine-grained, crystalline rock. This strengthening effect appears to be secondary to welding, as both fractures and deformation bands are found in crystallized, nonwelded units. Where present in the same outcrop, fractures and deformation bands generally occur in spatially distinct zones. This suggests spatial variations in the strength of crystallized, nonwelded units, consistent with variations in degree (i.e., weight percent secondary phases, which ranges from 1% to 24% in analyzed samples) and nature (i.e., weight percent cristobalite versus tridy-

[1]GSA Data Repository item 2003127, Table DR1, porosity and X-ray diffraction data, is available online at www.geosociety.org/pubs/ft2003.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

mite, whether or not crystallization is localized along grain margins) of postdepositional crystallization.

Within the ranges considered (Fig. 2), relative amounts of ash, pumice, phenocrysts, and lithic clasts do not affect mode of failure. However, these ash-dominated units may be mechanically distinct from more pumice- or lithic-rich ignimbrites.

Implications for Fluid Flow

The effect of deformation bands on nonwelded ignimbrite permeability has not been previously considered, because the structures were not previously recognized. Our observations allow us to make qualitative statements about the impact of these deformation bands on flow.

The variability of pore-throat geometry and pore connectivity in nonwelded ignimbrites causes highly variable saturated permeability (e.g., Rogers and Gallaher, 1995). Within deformation bands, cataclasis has reduced porosity, but potentially connected pores previously isolated within pumice vesicles. This increase in pore connectivity may be locally sufficient to increase fault permeability; however, the relative impact of porosity reduction versus increase in pore connectivity on saturated flow is unknown.

Pore-size reduction in deformation bands in nonwelded ignimbrites is likely to enhance unsaturated permeability because capillarity and water retention are inversely related to pore radius (Stephens, 1996). In the vadose zone of dry desert environments, the smaller pores in deformation bands in sand preferentially retain water (cf. Sigda and Wilson, 2003). Our hypothesis is supported by the presence of at least small amounts of smectite and carbonate in most deformation bands in the Los Alamos area. At most of these locations, the Bandelier Tuff has been above the water table since deposition (Purtymun and Johansen, 1974); therefore, preferential alteration and cementation of these fault zones is evidence of localized vadose-zone fluid transport. Preferential wetting of the zone of deformation bands observed at Busted Butte supports an interpretation of increased unsaturated fault-zone permeability (Fig. 1B).

CONCLUSIONS

The degree of welding and postdepositional crystallization determine whether a given ash-dominated ignimbrite unit deforms by formation of fractures or deformation bands. These characteristics are inversely proportional to porosity and directly related to grain-contact area and strength. These relationships between fault-zone structure and protolith petrophysical properties provide a basis for predicting fault-zone character from rock type, which is useful for fluid flow and transport models. Widespread fault-zone diagenesis records preferential vadose-zone fluid transport, suggesting that deformation bands in nonwelded ignimbrites enhance unsaturated fault-zone permeability. The magnitude of this increase and the density of deformation bands necessary to create significant flow paths for recharge and contaminant transport have not yet been determined. However, our work illustrates the importance of considering near-surface deformation of porous materials in understanding fault-zone effects on flow and transport.

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