PETROPHYSICAL CHARACTERIZATION AND
PERMEABILITY UPSCALING OF FAULT ZONES
IN SANDSTONE WITH A FOCUS ON
SLIP SURFACES AND SLIP BANDS

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Abstract

Strike-slip faults with slip magnitudes from several meters to kilometer scale developed by shearing of an echelon array of joints are considered in this study. Fault zone components within examined fault zones consist of deformed protolith (host rock, joints) and fault core (the fault rock, deformation and slip bands). The primary focus of the study is on texture and mineralogy of slip bands as well as on the assessment of the impact of slip surfaces and slip bands on upscaled fault zone permeabilities within the eolian Aztec Sandstone exposed in the Valley of Fire State Park of southern Nevada.

Slip bands in the Aztec Sandstone outcrops appear either reddish or whitish. The reddish slip bands are easily identifiable in the field. In contrast, amorphous silica filled bands are whitish in color and are not easily detected in the field. Petrographic and mineralogical analyses of slip bands using an optical microscope, X-Ray Diffraction, and scanning electron microscope showed that the reddish slip band infills are primarily hematite and the whitish slip band infills are amorphous silica – opal.

Slip bands form a hierarchical connected network within fault core, recording translation and rotation of fault rock blocks and fragments. Comparison of petrological characteristics of undeformed host rock samples away from the major faults and samples of deformed host and fault rock reveal differences in the texture as a result of strain localization in the vicinity of the faults as well as diagenetic alteration of the bands.

In this study I developed and applied computational rock physics approaches for petrophysical characterization of the fault components. I used the results of the petrophysical characterization in the permeability upscaling of fault zone blocks. Permeability of slip bands varies over 12 orders of magnitude as a function of degree of infill. The effect of this variation on selected fault zone permeabilities was evaluated by fluid flow simulation in two principal (normal and parallel to fault strike) directions using finite volume numerical simulations. Fully unstructured triangular grids were applied. The results show 2 orders of magnitude variation in upscaled fault zone permeability in the fault-normal direction and a factor of 2 variation in the fault-parallel direction. In addition, the numerical results presented here are compared to the earlier numerical results of Jourde et al. (2002) who used structured Cartesian grids for the numerical
simulations. The results obtained here are in qualitative agreement with these earlier calculations but use about a factor of 250-400 fewer numerical cells.
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Preface

The material covered in this dissertation incorporates techniques from the fields of structural geology, rock physics, petrology, and reservoir engineering to describe the textural, mineralogical and fluid flow properties of sheared joint-style faults in porous sandstone with particular emphasis on slip surfaces and slip bands. The dissertation consists of three chapters, all of which are individually discussed below. Each section of this thesis focuses primarily on one of these disciplines. Chapters 2 and 3 are meant as stand-alone manuscripts ready for peer-reviewed journal submission. Therefore, some material among chapters is repeated, mainly the introductory material.

Chapter 1 documents the geometric, textural and mineralogical description of fault zone components within the Aztec Sandstone with particular focus on slip bands. Petrologic analysis and SEM data for this project were collected by the author, while stable isotope and XRD data were obtained by Andreas Mulch and Stable Isotope Biogeochemistry Group at Stanford. A manuscript, based on this chapter, will be submitted to the Journal of Structural Geology for publication sometime in summer 2006 and will include Mulch and Aydin as co-authors.

Chapter 2 focuses on the development and application of computational rock physics approaches for petrophysical characterization of the fault components exposed in the Aztec Sandstone. In this chapter, undeformed host rock and fault zone components within the Aztec Sandstone such as deformed host rock, fault rock, and slip bands are characterized using image analysis and computational rock physics techniques applied to the thin section images. Portions of laboratory analyses for this study were carried out in the Stanford Rock Physics Laboratory under the guidance of Tapan Mukerji. Essential parts of this chapter will be submitted to Computers and Geosciences in June 2006 for publication under the title “Image analysis based porosity estimation from photomicrographs,” and will include Richa, Mukerji, Aydin and Mavko as co-authors.

Chapter 3 evaluates the effect of open and filled slip surfaces on the upscaled permeability of two fault zones with 6 and 14 m strike-slip in an eolian sandstone in the Valley of Fire State Park, Nevada. Fluid flow simulation and permeability upscaling of fault zones were carried out in collaboration with Mohammad Karimi-Fard under the
close supervision of Louis Durlofsky. This chapter was submitted to the *Hydrogeology Journal* in June 2006 for publication under the title “Permeability upscaling of fault zones in the Aztec Sandstone, Valley of Fire State Park, Nevada with a focus on slip surfaces and slip bands,” and is co-authored by Aydin, Karimi-Fard and Durlofsky.
Chapter 1
Slip surfaces and slip bands in the Aztec Sandstone, Valley of Fire State Park, Nevada

Abstract

The geometric, textural and mineralogical description of fault zone components within the Aztec Sandstone is documented. Each mature fault zone under consideration is composed of several fault components: a fault core, bounded by filled through-going slip surfaces referred to as slip bands, and a damage zone that contains joints, sheared joints and deformation bands. Slip bands in the Aztec Sandstone can be categorized into two predominant types: filled by iron-rich cement and partially filled by amorphous silica. Scanning electron microscopy of slip band infill showed that a major infill in iron-rich reddish slip bands is hematite. X-Ray Diffraction of partially filled whitish slip band is amorphous silica – opal. Slip bands filled by iron-rich cement are easily identifiable in outcrop due to the reddish-maroon color. In contrast, amorphous silica filled bands are whitish in color and are not easily detected in the field. Slip bands form a hierarchical connected network within fault core, recording translation and rotation of fault rock blocks and clasts. Petrologic characterization and comparison of undeformed host rock sampled away from the major faults with deformed host and fault rock reveal differences in the texture as a result of strain localization in the vicinity of the faults as well as diagenetic alteration of the bands and of other fault zone components.

Regional geology of the Valley of Fire State Park, Nevada

Strike-slip faults within the Aztec Sandstone are exceptionally well exposed in the Valley of Fire State Park, located in the North Muddy Mountains of Southern Nevada 60 kilometers NE of Las Vegas. The park is situated in the vicinity of the eastern edge of the Basin and Range extensional province within the Cordillera of Western North America. Two major fault systems related to Miocene Basin and Range deformation define the geologic setting in the locality of the Valley of Fire State Park (Figure 1.1). The left-lateral Lake Mead Fault System (LMFS) (Anderson 1973; Bohannon 1979) consists of
several lineaments with cumulative left-lateral offset of approximately 65 km (Bohannon 1984). LMFS was active between 16 Ma and 5 Ma (references in Duebendorfer et al. 1998). The right-lateral Las Vegas Valley Shear Zone (LVVSZ) (Longwell 1960) formed by several right stepping strands constitutes the Las Vegas Valley pull-apart basin (Campagna and Aydin 1994; Langenheim et al. 2001). Cumulative slip along the LVVSZ that occurred between 14 and 7.5 Ma (references in Duebendorfer 1998) is estimated to be in the range from 40 to 65 km (Bohannon 1984). Both fault systems were active contemporaneously as observed from mutual crosscutting relationships at their intersection in the Gale Hills which are close to the intersection of the LVVSZ and the LMFS (Çakir et al. 1998). Following the mapping by Anderson et al. (1994) and Çakir et al. (1998), the LVVSZ abuts against the more widespread LMFS.
**Figure 1.1.** Generalized map of Cenozoic faults in the Lake Mead region of southern Nevada. In general, the north to northeast trending faults are predominantly left-lateral strike-slip and the northwest trending faults are predominantly right-lateral strike-slip. Heavy lines are faults; dashed where inferred. Arrows indicate faults with primarily lateral slip sense. Ball and tick symbols indicate faults with primarily normal slip sense. *Inset:* Map of the United States. LMFS = Lake Mead Fault System, LVVSZ = Las Vegas Valley Shear Zone, BDM = Beaver Dam Mountains, FM = Frenchman Mountain, GB = Gold Butte, MM = Muddy Mountains, MRM = Mormon Mountains, SM = Spring Mountains, SR = Sheep Range, TSH = Tule Spring Hills, VM = Virgin Mountains, WR = Weiser Ridge. Base-image is a mosaic of 1:250,000 USGS DEMs (slightly modified from Flodin and Aydin, 2004)

Stratigraphic offsets indicate that the primarily strike-slip faults in the Valley of Fire State Park are similar to the two crustal-scale fault systems discussed in the previous paragraph. At present, the faults in the Valley of Fire State Park (Figure 1.2) are believed to be inactive based on a lack of recent surface deformation and seismicity in the surrounding area (Rogers and Lee, 1976). However, sparse earthquakes in the vicinity of the western lobe of Lake Mead point to right-lateral slip on north-trending faults.

**Geologic setting of and faulting mechanisms in the Aztec Sandstone**

The Aztec Sandstone was deposited in a back-arc basin from late Triassic to Middle Jurassic period (Bohannon 1983; Marzolf 1983). The Aztec Sandstone is laterally correlated with the Navajo Sandstone exposed in large areas in the state of Utah (Blakey 1989). The stratigraphic thickness of the Aztec Sandstone exposed in the Valley of Fire is up to 1400m (Bohannon 1983; Marzolf 1983, 1990). Texturally, it is a well-sorted quartz arenite with average grain size of 0.25mm, porosity values ranging between 16-25% and permeabilities from 123 to 5991 mD (Antonellini and Aydin 1994; Flodin et al. 2003; 2005). The Aztec Sandstone is part of a Mesozoic clastic sequence that is underlain by upper Paleozoic carbonates and shales (Bohannon 1983). Triassic red beds of the Moenave, Chinle and Moenkopi formations, with a total thickness of up to 2100 m (Bohannon 1977), are composed of sand-, silt-, and mudstone (Marzolf 1990). The conglomerate that forms the base member of the Cretaceous Willow Tank Formation forms an unconformity with a discordance of locally up to 10° overlying the Aztec Sandstone (Eichhubl et al. 2004).

Two dominant steeply dipping fault sets with opposite sense of shear were developed in the Valley of Fire (Figures 1.2). Both fault sets, a right-lateral set of faults oriented SE-
NW and a left-lateral set that strikes S-N, crosscut each other. Strike-slip faulting postdates extensive formation of deformation bands associated with the Cretaceous Sevier Orogeny that predates jointing (Myers and Aydin 2004).

Sheared joint-based faulting

Two mechanisms are responsible for fault formation in porous sandstone (Myers 1999). Deformation band-based faulting is a progressive process that initiates by localization and amalgamation of individual deformation bands subsequently forming a zone of deformation bands. Throughout this stage, short, segmented slip surfaces that accommodate discrete offsets begin to nucleate (Shipton and Cowie 2001). As strain localization progresses, slip surfaces and deformation band zones coalesce to form through going deformation band style faults (Aydin and Johnson 1978; Antonellini and Aydin 1995; Shipton and Cowie 2001). Sheared joint-based faulting is a hierarchical and progressive process that involves shearing along preexisting joints and joint zones, and produces secondary and higher order joints, fragmented rocks, and fault rocks (shown in Figure 1.3 and described by Myers 1999 and Myers and Aydin 2004).
Figure 1.2. Location map of the study area with two sets of strike-slip faults (slightly modified from Flodin and Aydin 2004). The location of the faults examined is marked by red circles. Metric value in the red boxes corresponds to the amount of lateral slip along the individual faults.
Consequently, splay fractures were subjected to shear resulting in the formation of newer generations of splay fractures. This process is hierarchical and continuous for several stages of fracturing. Throughout this process, the fault core and surrounding damage zone expand. The fault core contains and is bounded by slip surfaces and is surrounded by the fault damage zone (Figure 1.4).
Figure 1.4. (A) Photograph of the characteristic structural features of the fault core (fault rock and slip surfaces) and the surrounding damage zone (joints and sheared joints) associated with a fault with 150 m slip. Geologic hammer for scale. From Jourde et al. 2002. (B) A typical fault zone with 8 m slip and with a well developed fault core exposed in the Aztec Sandstone. Fault rock is bounded by and contains through going slip surfaces. Pencil for scale.

Fault zone components

Strike-slip faults with a minor dip-slip component in Aztec sandstone in the Valley of Fire formed by a hierarchical progression of shearing along preexisting joint zones consist of a number of fault components. For sheared joint based faults, the initial shearing of joints is followed by the formation of zones of damaged host rock (fragmented rock) at joint stopovers and bends and newly formed splays propagating from preexisting joints (Davatzes and Aydin 2003; Myers and Aydin 2004; Flodin and Aydin 2004). As shear strain increases, this process is progressively repeated with accompanying crushing of fragmented rock and formation of isolated pockets of fault rock. As a result, a through going slip surface develops within the discontinuous fault rock pockets that form a continuous seam along the fault.
Damage associated with shear-joint faults can be divided into an outer fault damage zone and inner fault core inserted into a protolith (Caine et al. 1996; Aydin 2000 and Flodin et al. 2005) (Figure 1.5).

Fault zone components in the fault core consist of sheared joints, deformation bands, fragmented rock, fault rock, and slip surfaces, while damage outside of the core is in the form of joints, sheared joints and deformation bands (Myers and Aydin 2004). Because this study evaluates the role of the slip surfaces within the fault core, I primarily focus on the two elements: slip surfaces and fault rock as well as the deformed and undeformed host rock from which these components were derived. The characteristics of joints and deformation bands in relation to joint-based faults and their hydraulic properties in sandstone are described by Myers (1999), Taylor et al. (1999), Taylor and Pollard (2000) and Sternlof et al. (2004; 2006).

**Outcrop description of slip surfaces**

In outcrop, the fault core is defined as a zone of fault rock and intensely fragmented pockets of host rock that is both divided up and bound by slip surfaces along which the majority of the slip has occurred (Figure 1.6).
Deformed host rock is divided by a network of slip surfaces and joints (Figure 1.7) into blocks or clasts of various size with in-situ identifiable sedimentary cross-bedding. In some cases, fragmented rock is adjacent to but separated from the main body of host rock by sheared joints and slip surfaces, while in other cases the fragmented rock is completely isolated from the main host rock body by fault rock (Flodin et al. 2005). Unlike deformed host rock, fault rock visually lacks recognizable sedimentary bedding and is characterized by grain size reduction (as determined with a hand lens). Color contrast between host and fault rock is often prominent in the outcrop. In most cases, fault rock is lighter (whitish) in color and bounded by or contains slip surfaces that cut across individual bodies of fault rock. The slip surfaces are the most continuous elements within the fault zone. They are planar in map view and are by and large identifiable by mm-wide reddish iron-reach staining. Slip surfaces are usually smooth to the touch, and in some cases show kinematic indicators (i.e., slickensides).
Figure 1.7. (A) Photograph of deformed host rock blocks translated and rotated by bounding slip surfaces. Amount of slip and rotation are visible in outcrop based on the displacement of the diagenetic bands (reddish). (B) Map of deformed host rock blocks by slip surfaces of varying orientation. (C) Rotation as a function of the distance from a major through going slip surface. Pencil for scale.
As indicated above, as a result of diagenetic processes, most slip surfaces are tabular zones of varying degrees of mineral infill bounded by two planar boundaries. Therefore, hereafter we will refer to slip surfaces as slip bands.

In the field, slip band lengths range from several centimeters to several tens of meters, while their widths range from 0.1 to 1 mm. Slip bands form as single features, but in some cases individual slip bands may merge into a zone and may evolve into a set of slip bands (Figure 1.8). Slip band density may vary dramatically along a single fault reaching its maximum value within the widest zones of well-developed fault rock (Figure 1.9).

**Figure 1.8.** Photograph of a sample from a fault zone in the Aztec Sandstone. Sample is 20cm long. fr - fault rock; dhr - deformed host rock; sb - slip band; sbs – slip band set.
Figure 1.9. (A) Photograph of the well-developed fault rock within 14m slip fault zone with numerous slip bands. (B) Closer map view depicting density of slip bands and older slip bands offset by younger ones. Pencil for scale. fr - fault rock; dhr - deformed host rock; sb - slip band.

Slip band densities of well-developed zones can exceed 10 per 10 cm in both fault-parallel and fault-perpendicular directions. The hierarchical evolution of slip band networks within the fault with 14 m left-lateral slip is shown in Figure 1.10. The first generation slip bands were sheared in a left-lateral sense by second generation slip bands, which were later sheared in a right lateral sense to form third generation slip bands. This process is further repeated to form newer generations of slip bands and is related to the evolution of fault zones as some slip bands become inactive and new ones form to accommodate slip. A similar mechanism for fault development by sheared joints is documented by Myers and Aydin (2004) and Flodin and Aydin (2004).
Figure 1.10. Hierarchical relationship between 5 generations of slip bands within the core of the 14 m left lateral slip fault. A. Map by Nickolas Davatzes. B. Photograph and (C) schematic representation of a portion of the fault core and slip bands. Pencil on photograph is 13 cm long.

Fault rock and slip bands texturally are highly heterogeneous components of the fault zones, and were subjected to the cataclastic and diagenetic alteration due to the mechanical and paleofluid flow activity (Taylor et al. 1999; Eichhubl et al. 2004) throughout the fault zone evolution. Consequently, the petrophysical properties (discussed in Chapter 2 of this dissertation) of slip bands, such as porosity, permeability and connectivity, do not remain constant throughout the fault evolution.

Optical microscopy study

Twenty hand specimens were collected from 5 strike-slip fault zones with maximum offsets ranging from 6 m to 2 km. More than 30 petrographic thin sections were prepared. Thin sections were blue epoxy impregnated under vacuum in order to better characterize pore space. For reliable representation of anisotropy within the fault zone, thin sections
were cut in two orthogonal directions: one parallel and the other perpendicular to the fault strike. Sections were analyzed using an optical microscope with a digital camera attachment. Several hundred high resolution (1520x1080) photomicrographs were imaged and processed.

**Host rock, deformed host rock and fault rock petrology**

Differences between host rock, deformed host rock and fault rock samples representing various strain and diagenetic alteration levels are apparent at the microscopic scale (Figure 1.11). Undefomed host rock samples (Figure 1.11a) collected away from the major faults do not show noticeable grain fracturing. In deformed host rock samples collected from damage zone most grains are not fractured, however, they exhibit concavo-convex grain contact (Figure 1.11b) as evidence of strain localization. In contrast, samples collected from the deformed host rock in the vicinity of a slip band (Figure 1.11c) typically show grain fracturing. The sample shown in Figure 1.11d was collected from a small pocket of deformed host rock contained in the fault rock. Many of the grains in this sample are fractured. However, they preserve their original shape, location and nearly all of the pore space remains unoccupied. Elsewhere in this sample, regions of virtually undeformed host rock were observed.
Figure 1.11. Photomicrographs of variously deformed and altered Aztec Sandstone. (a) Undeformed host rock lacks intense grain fracturing. (b) Deformed host rock sample with concavo-convex grain contact (c) deformed host rock in the vicinity of a slip band exhibiting intense grain fracturing (d) deformed host rock from small clast inserted into the fault rock with fracturing of most of the grains and preservation of original shape, location and nearly all of the pore space (e) Slip band bounded by fault rock on the left side and deformed host rock on the right side. The region to the left of the slip band accommodates the most strain (f) Fault rock showing extensive grain crushing and porosity collapse with few survival grains. a, b and d are in crossed polarized light. c, e and f are in plain view.
Figure 1.11 (cont-d). Photomicrographs of variously deformed and altered Aztec Sandstone. (g) Fault rock sample showing dissolved capillary meniscus (indicated by arrow) of iron-rich cement (brownish in color). (h) Fault rock in the vicinity of slip band shows fractured and sheared grain (i) Dissolution of quartz grain within fault rock (indicated by arrow) (j) Deformed host rock in the vicinity of the slip band. Grains are extensively fractured, portions of grains are translated along fractures, pressure solution in quartz grains is observed. (k) Deformed host rock in the vicinity of the slip band. Grains show preferential orientation, extensive fracturing and dislocation (m). Deformed host rock sample with evidence of quartz grain dissolution and silica cement precipitation (indicated by arrows). g, i and m are in crossed polarized light. h, j and k are in plain view.
An example of a higher level of strain in deformed host rock is shown in Figure 1.11c. Here, many of the grains are almost completely fragmented and much of the porosity has collapsed or has been filled by smaller angular grains; with no remaining survival grains. A slip band bounded by fault rock (on the left side) and deformed host rock (on the right side) is shown on Figure 1.11e. Based on the greatest reduction in grain size, the region to the left of the slip surfaces appears to have accommodated the most strain. Here, pore space is nearly absent; grains are extensively fractured with few survival grains. To the right of the slip surfaces larger pores are apparent; individual grains are slightly more elongated in shape and indicate weak grain alignment. Fault rocks are the most deformed samples examined (Figure 1.11f) as a result of a severe grain size and porosity reduction, which is interpreted as evidence for varying strains and dissolution-precipitation processes.

Most of the grains within samples of host rock and deformed host rock do not appear to have undergone substantial grain rotation and/or translation, based on original grain roundness and outlines of remnant grain coating cements (iron-oxides, hydroxides) which are preserved. In contrast, samples of fault rock and deformed host rock collected in the vicinity of slip bands (Figure 1.11h, 1.11j and 1.11k) show intense grain fracturing and associated grain dislocation and translation, as an evidence for localization of strain. Diagenetic alteration is apparent in Figure 1.11g, 1.11i and 1.11m. Here, quartz grains as well as capillary meniscus of iron-rich cement are dissolved, and in some cases, silica cement precipitated in-situ (Figure 1.11m).

**Slip band petrology**

Within the fault zones in the Aztec Sandstone, two slip band infill textures are documented: slip bands partially filled by whitish amorphous silica cement (Figure 1.12a) and bands filled by reddish-maroon iron-rich cement (Figure 1.12b).
Figure 1.12. (A) Slip band partially filled with silica cement. (B) Coalescence of the three distinct slip bands into one zone. Here, slip bands are filled with iron-rich cement. Blue color denotes pores filled by resin epoxy. View in the plane polarized light.

Amorphous infill within the slip bands consists of sub-micron size cement and occasionally contains angular grain fragments with rare survival quartz grains. As is apparent from Figure 1.13, porosity is dramatically decreased, if not completely absent.

Figure 1.13. Close view of amorphous silica bridge between two pore lenses shown in Figure 1.12.A. The band is bounded by well cemented walls from both sides. Note porosity difference between the band and the adjacent fault rock.

The walls of the slip band contain coarser grains and are better cemented by iron-rich cement than amorphous infill within the central part of the band as shown in Figure 1.14.
Figure 1.14. Photomicrographs of slip band from 14 m slip fault zone. The band contains pore lens and is bounded by well cemented walls from both sides. Upper image in cross-polarized light. Lower image in plain view.
The shape of pore lens suggests that dissolution of amorphous silica within the band is favored in the direction parallel to the band, which I interpret based on the difference in solubility between less stable amorphous silica and more stable quartz grains (Williams et al. 1985). In contrast to the slip band infill type described above, slip bands that contain iron-rich cement, are more heterogeneous texturally. Most of the band infill is composed of the extensively crushed fragments of quartz grains supported in the iron-rich cement matrix (Figure 1.15). Here, grains are poorly sorted and in most cases do not show preferential alignment with respect to the direction of shear along the bands. Cemented walls of the band observed in the previous cases are absent.

![Figure 1.15. Photomicrograph of slip band from 14 m slip fault zone in plain view. Band is filled by iron-rich matrix that supports highly angular grain fragments.](image)

Iron-rich cement infill is primarily localized within the slip bands and generally absent within the adjacent fault rock (Figure 1.16). Porosity, grain sorting and grain size difference, as well as the difference in grain contact between slip bands and fault rock suggests the externally derived nature of slip band infill.
Figure 1.16. Photomicrographs of two parallel slip bands in fault rock of 14m fault. Slip bands filled with light brownish iron-rich cement. Pocket of fault rock between slip bands lacks mineral infill. Note porosity difference between slip bands and fault rock. Upper image in cross-polarized light. Lower image in plain view.
Mineralogic, textural and petrologic characterizations based on Adams et al. (1984), Perkins and Henke (2004) and Pettijohn et al. (1987) of slip band and fault rock in comparison to the host rock are summarized in Tables 1.1 and 1.2. Textural maturity is a function of three variables: matrix content, sorting, and clast shape. Mineralogical maturity is shown by the proportion of minerallogically stable grains in the rock. Strain (anomalous) extinction documented in fault rock, deformed host rock in the vicinity of a major slip band and absent within the slip band suggests that grains present within the slip band were not subjected to internal strain.

### Table 1.1. Clay matrix, sorting, roundness, porosity, cementation and maturity (mineralogical and textural). hr – host rock; dhr – deformed host rock; dhr at sb – host rock close to major slip band; fr – fault rock; sb – slip band.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Clay matrix, %</th>
<th>Sorting</th>
<th>Roundness</th>
<th>Mineral. Maturity</th>
<th>Textural Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>hr</td>
<td>&lt;5</td>
<td>Very well</td>
<td>Rounded</td>
<td>mature</td>
<td>supermature</td>
</tr>
<tr>
<td>dhr at sb</td>
<td>&lt;5</td>
<td>Very well</td>
<td>rounded</td>
<td>mature</td>
<td>mature</td>
</tr>
<tr>
<td>sb</td>
<td>&gt;50</td>
<td>Poor</td>
<td>Angular</td>
<td>Immature</td>
<td>Immature</td>
</tr>
<tr>
<td>fr</td>
<td>&lt;5</td>
<td>Moderate</td>
<td>Subrounded-angular</td>
<td>Submature</td>
<td>Submature-mature</td>
</tr>
</tbody>
</table>

### Table 1.2. Sphericity, grain contact, pleochroism, relief, extinction. hr – host rock; dhr at sb – host rock close to major slip band; fr – fault rock; sb – slip band.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sphericity</th>
<th>Grain Contact</th>
<th>Pleochroism</th>
<th>Relief</th>
<th>Extinction</th>
</tr>
</thead>
<tbody>
<tr>
<td>hr</td>
<td>medium</td>
<td>Point-long</td>
<td>no</td>
<td>low</td>
<td>No cleavage</td>
</tr>
<tr>
<td>dhr at sb</td>
<td>low</td>
<td>Point</td>
<td>no</td>
<td>Low</td>
<td>strain</td>
</tr>
<tr>
<td>sb</td>
<td>low</td>
<td>Matrix supported</td>
<td>no</td>
<td>Low</td>
<td>No cleavage</td>
</tr>
<tr>
<td>fr</td>
<td>low</td>
<td>Point-long</td>
<td>no</td>
<td>low</td>
<td>strain</td>
</tr>
</tbody>
</table>

**Scanning electron microscopy study**

In order to analyze the mineralogical content of slip band infill, Scanning Electron Microscopy (SEM) distance traverse point count data corresponding to Si, O$_2$ and Fe rich minerals were analyzed (Figure 1.17). Counts were sampled along three transects perpendicular to two different slip bands in the fault core of the fault with 14 m slip. Analyses showed strong peaks in Fe-rich mineral cement (goethite/hematite mixture) and
corresponding decrease in Si and O\textsubscript{2} rich mineral cement. Similarly, Eichhubl et al. (2004) documented iron-rich infill in undeformed parts of the Aztec Sandstone. X-Ray Diffraction (XRD) analysis by Eichhubl et al. (2004) showed the widespread occurrence of predominantly goethite and hematite.

![Backscatter secondary electron image along two scanlines across two slip bands (oriented vertically on a and b) within the core of the fault with 14 m left lateral slip and corresponding response (shown on a' and b') to Fe, Si and O\textsubscript{2} rich elements along the transects (denoted by yellow area). Note strong peak of hematite/goethite (increase in Fe) infill along both transects and relative reduction in Si and O\textsubscript{2}.

**Figure 1.17.**

Hematite, as well as fractions of goethite has been documented in eolian environments of the Colorado Plateau (Chan et al. 2000; Eichhubl et al. 2004; Beitler et al. 2005). Similarly, Walker et al. (1981) documented hematite grain coating within the red beds of the Triassic Moenkopi Formation. The X-Ray Diffraction (XRD) analyses performed on the sample of the whitish infill showed a strong peak corresponding to amorphous silica and is believed to be opal (personal comm. D. Lowe, Stanford University).
University, 2005). The matrix supported nature of the cement within the slip bands (Figure 1.18) and the origin of the fluids responsible for the precipitation of the cement are currently under investigation.

![Figure 1.18. XRD. Strong peaks correspond to quartz and oxide rich components. Whitish infill in slip band is believed to be amorphous silica-opal.](image)

**Conclusions**

Field characterization of slip bands shows that slip bands are the most continuous elements present within fault zones. Their geometry records individual block rotation and translation within the fault core. Slip bands form as individual features that may evolve into sets or zones of slip bands. The hierarchical evolution of slip band networks within fault zones is documented. The first generation slip bands were sheared in a left-lateral sense by second generation slip bands, which were later sheared in a right lateral sense to
form third generation slip bands. This process is further repeated to form newer
generations of slip bands and is related to the evolution of fault zones as some slip bands
become inactive and new ones form to accommodate slip.

Petrologic analyses of undeformed host rock, deformed host rock, and fault rock
clearly demonstrates the differences in grain size, sorting, porosity and strain localization.
Petrophysical properties of fault zone components are discussed in detail in Chapter 2 of
this dissertation. Laboratory analyses reveal the complicated nature of slip bands and
show traces of diagenetic processes that took place within the fault zone, resulting in
dissolution and precipitation of silica and iron rich minerals and the subsequent alteration
of slip band permeability. Scanning electron microscopy of the reddish slip band infill
shows a relative increase of iron rich minerals, likely hematite, and a decrease of oxygen
and silica rich minerals. X-Ray diffraction analysis of a sample with whitish slip band
infill shows strong peaks corresponding to the amorphous silica and oxide rich
components, which is interpreted as opal. The matrix supported nature of material present
within the slip bands suggests fluid-based transport of infill.

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oxides, -hydroxides from grain surfaces. This work greatly benefited from many
discussions with Ghislain De Joussineau and Fabrizio Agosta. The staff of the Valley of
Fire State Park, Nevada Parks Division is thanked for their welcoming support.

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Antonellini, M., and Aydin, A., 1994, Effect of faulting on fluid flow in porous sandstones;


Chapter 2
Petrophysical characterization of fault zone components in the Aztec Sandstone, Valley of Fire State Park, Nevada

Abstract

Fault zones in sandstone are highly heterogeneous features due to mechanical and diagenetic processes throughout the fault evolution. A typical fault zone within the Aztec Sandstone is composed of several fault components: fault core, which contains comminuted material interlaced and bounded by through-going slip bands, and a damage zone which is composed of joints, sheared joints and deformation bands. Accurate representation of petrophysical properties of fault zone components in flow models is of great importance for the proper management of petroleum reservoirs and groundwater aquifers. To this end, porosity and permeability values of fault components should be accurately estimated. This is generally a challenging task, as porosity and permeability are difficult and expensive to measure directly due to the limited thicknesses (<1 cm) of some fault zone components such as deformation and slip bands. Direct fault rock porosity and permeability measurements are also difficult because of the fragility and weakness of fault rock material. However, consistent and inexpensive estimates can be obtained by Lattice-Boltzmann flow simulations with 3-D reconstruction of the pore geometry from thin-section image analysis methods. In this work I developed and applied computational rock physics approaches for petrophysical characterization of the fault components exposed in the eolian Aztec Sandstone of southeastern Nevada. The results of this study demonstrate the importance of careful petrophysical characterization of fault zone components and are used in the permeability upscaling of fault zone blocks discussed in detail in Chapter 3 of this dissertation.

Introduction

Fractures and faults are the most ubiquitous and efficient avenue for hydrocarbon migration as well as entrapment (Aydin 2000). Modeling of fluid flow in fractured and faulted reservoirs requires realistic input data that are based on both careful field
description and detailed characterization of structural and petrophysical properties of fault components. Hydraulic properties of fault components play a crucial role in fluid migration through and in the vicinity of faults. In an effort to better characterize the fault zone components in sandstone, I have been investigating an analog reservoir in the Valley of Fire State Park, Nevada. By and large, the dominant methods of characterizing hydraulic properties of faults and fractures in exploration are those that employ seismic and borehole data. However, detailed characterization of fault hydraulics is not satisfactorily recovered using the aforementioned methods. Thus, studies based on hydraulic analysis of faults in analog reservoirs provide valuable information.

The Aztec Sandstone exposed in Valley of Fire State Park represents a unique combination of rich paleofluid flow and extensive strike-slip faulting history. Myers and Aydin (2004) developed models for fault evolution in the Aztec Sandstone based on the hierarchical occurrence and shearing of splay fractures. Flodin and Aydin (2004) further investigated the formation mechanism for strike-slip faulting and proposed a conceptual model for fault network evolution. Jourde et al. (2002), Flodin et al. (2004) and Ahmadov et al. (submitted) computed upscaled permeabilities from outcrop-based measurements. Flodin et al. (2005) determined various petrophysical properties of the host and the fault rock of the Aztec Sandstone using laboratory methods. The results of these studies suggest that detailed characterization of the fault components has a major impact on flow in the vicinity of the faults. This study is an extension of the previous efforts in the characterization of the fault zones in the Aztec Sandstone and their permeability upscaling. I focus on the textural and petrophysical characterization of fault zone components in order to better evaluate their role and representation in flow models.

Most conventional tools available for estimating porosity, permeability and grain size distribution require coring of plugs or in-situ measurements. Permeability estimation based on the gas permeametry of core samples requires core to be several centimeters in both diameter and length. In homogeneous sandstone, porosity and permeability are relatively easy to measure. However, the limited thickness and fragility of the fault zone components such as fault rock and slip bands limits use of conventional methods of porosity and permeability estimation. In light of this, I present several methods for porosity, permeability and grain size distribution estimation based on the image analysis
of photomicrographs obtained from thin sections. Image analysis techniques proved to be powerful, fast and non-destructive methods for various types of applications. Antonellini and Aydin (1994) used image analysis for pore network characterization in fault rocks. Thin sections are relatively inexpensive and easy to obtain. In order to differentiate pores from grains and cements, thin sections are impregnated by colored epoxy resin (usually blue colored epoxy). Once thin sections are prepared, areas of interest are imaged using a camera attached to a regular optical microscope.

The methods developed and used in this study are based on the principles of computational rock physics and image analysis of photomicrographs. I present a method for grain size distribution estimation, two methods of porosity computation, and apply the package of algorithms for permeability computation, Digital Rock® (Keehm et al. 2001; 2004), based on the Lattice-Boltzmann flow simulation method.

**Geologic setting and fault zone components**

Strike-slip faults within the Aztec Sandstone are exposed in the Valley of Fire State Park, located in the North Muddy Mountains of Southern Nevada 60 km NE of Las Vegas (Figure 2.1). The Aztec Sandstone is Jurassic eolian sandstone that was deposited in a stable cratonic setting along the western margin of North America (Marzolf 1983). It is laterally correlated with the Navajo sandstone exposed in Utah (Blakey 1989). The Aztec Sandstone is 800 to 1400 m thick and is a well-sorted fine to medium-grained quartz arenite with average porosity values of 15-25 % and permeabilities up to 6 D (Flodin et al. 2005).
Figure 2.1. Location map of the study area with two sets of strike slip faults (slightly modified from Flodin and Aydin 2004). The location of the examined faults is marked by red circles. Metric values in the red boxes correspond to the amount of lateral slip along the selected faults.

Fault zone components (Figure 2.2) in a typical fault zone in the Aztec Sandstone consist of deformed protolith (host rock, joints) and fault core (the fault rock, deformation and slip bands). Fault rock, deformation and slip bands are highly
heterogeneous components of the fault zones, and were subjected to the cataclastic and diagenetic alteration due to the mechanical and paleofluid flow activity throughout the fault zone evolution. Petrophysical properties of deformation band arrays and their permeability effects in the Aztec Sandstone were addressed by Sternlof et al. (2004).

Figure 2.2. Photograph of the sample from the fault zone in the Aztec Sandstone. Sample is 20 cm long. Note that deformation bands and joints are not present in this sample.

Slip bands are thin tabular features localized between deformed host and fault rock shown in Figure 2.3. Slip band lengths range from several centimeters to several tens of meters. The average slip band widths range from 0.1 to 1.5 mm.

Figure 2.3. Photomicrograph of slip band filled by hematite-rich cement. View in plane light.
In order to characterize and capture geometric, textural, and mineralogical heterogeneity within the fault zones in the Aztec Sandstone, I employed several techniques. Twenty hand specimens were collected from 5 strike-slip fault zones with maximum offsets ranging from 6 m to 2 km out of which more than 30 petrographic thin sections were prepared. Thin sections were polished and blue epoxy impregnated under vacuum in order to better characterize pore space. For reliable representation of anisotropy within the fault zone, thin sections were cut in two orthogonal directions: one parallel and the other perpendicular to the fault strike. Sections were analyzed using an optical microscope with a digital camera attachment. Several hundred high resolution (1520x1080) photomicrographs were obtained and processed.

**Porosity estimation methods**

Two general methods of porosity estimation were employed in this study. Porosity values were obtained from a binary image of the original photomicrograph and by classification of the indexed version of the original photomicrograph.

Prior to porosity estimation using methods described in this paper, simple thresholding of the original image (Figure 2.4) was performed in order to estimate the range of variation in porosity values. Richa et al. (2005) and Ahmadov et al. (in prep.) discussed several methods of porosity estimation from thin section photomicrographs based on the threshold, parameter classification and application of neural networks to the images.

![Figure 2.4. Original photomicrograph of the host rock in the Aztec Sandstone. View in plane light.](image)
Once the original image is downloaded, it is converted into a black and white image and a threshold is automatically applied. This simple operation estimated porosity value close to 31%, which is most likely an overestimation. Another threshold was applied to the different color planes of the true-color RGB (red-green-blue) image. First, red color plane was thresholded and after conversion into a black and white image, the porosity value was reduced to 22.8%. Thresholding of green and blue color planes resulted in porosity values close to 9.4 and 11.2%, respectively. Use of simple thresholding of different planes of the RGB image yielded the range of porosity values between 9.4 and 31%. This is too wide of an estimation range of porosity values. Therefore, further investigation was conducted in order to narrow this range to a few percent.

Porosity estimation by conversion into binary image

The first method requires transformation of the original color image into an indexed image with 10 colors. Each of these colors corresponds to one of three domains identified in the photomicrograph: pores, grains and hematite-rich cement (brownish to reddish color bridges between grains in Figure 2.4). Therefore, each color was assigned its corresponding domain. The main reason beyond conversion into ten colors prior to the indexing of three main domains is due to the fact that domains are better represented if the number of colors in the color map is more than the number of indexes in the final version of the indexed image. Conversion into a binary image yielded a porosity value of 17.6%. Though this value lies within the reasonable range of porosities, many artifacts introduced during conversion result in relative inaccuracy of the porosity estimation. Figure 2.5 shows the binary image with a large number of isolated pixels that do not belong to the surrounding domain, whether it is pore or grain.
Two morphological structure elements were created to eliminate single ‘xenopixels’. These include flat diamond-shaped and square-shaped structuring elements with sizes equal to 1 and 2 pixels, respectively (Haralick and Shapiro 1992; van den Boomgaard and van Balen 1992). A total of four morphological operations based on erosion and dilation were performed, thus giving a better representation of the image. The porosity value reached 18.7 %, after the application of morphological operations (Figure 2.6).
directions of the image versus porosity values. A binary digital image may be represented by an indicator function \( f(q) \) as follows:

\[
f(q) = \begin{cases} 
1 & \text{if } q \text{ belongs to the pore space,} \\
0 & \text{otherwise},
\end{cases}
\]  

(1)

where \( q \) denotes a spatial location in the binary image. The 2-D correlation block computes the two-dimensional autocorrelation of the input matrix (digitized photomicrograph). Assume that matrix \( T \) has dimensions \((M, N)\). The equation for the two-dimensional discrete autocorrelation is

\[
C(i, j) = \sum_{m=0}^{(M-1)} \sum_{n=0}^{(N-1)} T(m, n) \overline{T(m + i, n + j)}
\]  

(2)

where \( C \) is the autocorrelation matrix and \( 0 \leq i < 2M - 1, 0 \leq j < 2N - 1 \).

Figure 2.7. 2-D autocorrelation as a function of porosity, blue denotes \( x \) and red \( y \) direction, respectively. (a) – erosion, (b) – dilation, (c) – erosion, (d) – dilation, (e) – erosion.
The lack of the difference in the behavior of the cross correlation values with respect to porosity may be attributed to the fact that all images were derived from the original black and white image through morphological operations. Nevertheless, results clearly demonstrate that there is no significant anisotropy in \( x \) and \( y \) directions between all 5 images, therefore proving morphological operations such as dilation and erosion to be useful tools that remove ‘xenopixels’ without anisotropic artifacts.

**Porosity estimation by classification of Red-Green-Blue (RGB) image**

The classification method developed here requires identification of two main parameters: training data and group corresponding to the training data. Using the training data, new sample data can be statistically classified into the appropriate group. Sample and training must be matrices with the same number of columns. Group is a grouping variable for training data. Its values define groups, and each element defines the group to which the corresponding row of training belongs. Class (output of classification) indicates which group each row of the sample has been assigned to, and is of the same type as group. Therefore, prior to the classification, the original photomicrograph was reshaped to meet the requirements of the classification procedure.

Training data included 50 pixel values from 3 different domains: pores, grains and hematite-rich cement. The amount of training points within each distinct domain was chosen based on the approximate ratio of occurrence of different domains within the image resulting in 15, 30 and 5 values for pores, grains and hematite-rich cement, respectively. For simplicity of procedure, group was formed with values of 1, 2 and 3 corresponding to pores, grains and hematite, respectively. Once data was converted into recognizable double precision format, it was classified by groups and resized back into a matrix with original dimensions. The classification was based on the standard discriminant analysis. Porosity of classified data was estimated as a ratio of the amount of pixels that correspond to the pore group (group 1, with value 1) to the total amount of pixels. Porosity estimated by classification method yielded a value of 17.7 %, which agrees very well with the result of the previous method (18.7 %). Thus, the range of porosity values estimated by the two methods presented here was reduced to 1 %. Even though porosity estimation procedure was applied to a single photomicrograph, the
results obtained here are promising. Further development of the technique as well as its application to a statistically reliable number of photomicrographs is currently under investigation (Ahmadov et al. in prep.)

**Grain size estimation**

For grain size distribution estimation, four photomicrographs of fault components were used (Figure 2.8). Photomicrographs were obtained from thin sections of host, deformed host and fault rock.

![Figure 2.8. Four photomicrographs used in grain size distribution estimation. Host rock (a), fault rock (b), deformed host rock (c and d). Note the grain size difference in two deformed host rock samples (c and d) and poor sorting in fault rock sample (b). View in crossed polarizers.](image)

Methods of grain-size analysis of sediments include mechanical sieving (Krumbein and Pettijohn 1938), settling through a column of water (Syvitski et al. 1991) or laser diffraction (Agrawal et al. 1991). Rubin (2003) employed a simple autocorrelation algorithm for determining grain size from digital images of sediment. As an alternative to
the aforementioned methods, I provide a fast and inexpensive technique based on the image analysis of thin sections.

Grain size distribution is estimated using a modified numerical algorithm of digital sieving in MATLAB® that computes the size distribution in the photomicrograph without explicitly detecting particular grain boundaries. The intensity surface area distribution of grains is estimated as a function of size. This technique mimics mechanical sieving of grains using decreasing sizes of digital sieves and collecting what remains after each sieve size. First, the image is enhanced to better reflect the intensity range, then a series of disc-shaped filters with gradually decreasing diameter is used for sequential sieving of the image, and finally cumulative area values are plotted as a function of disc (grain) diameter. Figure 2.9 shows results of grain size distribution computation as a function of grain area for four samples. The wide range of grain size distribution in two deformed host rock samples adjacent to the fault core is due to the varying grain sizes attributed to the cataclastic deformation.

![Figure 2.9. Grain size distribution for four samples. Host rock (a), the fault rock (b) and the deformed host rock (c and d).](image-url)
Permeability computation using Lattice-Boltzmann method

Most of the common permeability prediction methods are empirical and are based on simplified pore geometry representations (e.g., the Kozeny-Carmen relation, Bear 1972). Archie (1950) proposed a method for permeability estimation based on the electrical resistivity of rock and fluid that saturates porous medium, porosity, lithologic and cementation factors. Worthington (2001) showed a directional dependence of Archie’s law, which occurs because the formation factor is a function of the tortuosity of the porous media. The relationship of permeability to porosity, specific surface area, geometrical and formation factors was demonstrated by Walsh and Brace (1984). Blair et al. (1996) employed an image processing technique to estimate porosity and specific surface area in sandstone. They applied the empirical relationship suggested by Walsh and Brace (1984) for porosity and specific area values.

Although these methods are capable of reasonable permeability estimation, they depend on several parameters that are not easily obtained from photomicrographs. In particular, specific surface area is scale sensitive, the formation factor is estimated based on the electrical properties of rocks and geometrical and cementation factors are not directly obtained from thin-section images.

3-D pore geometry reconstruction

As an alternative to the aforementioned methods, I use a technique based on image processing and computational rock physics (Keehm et al. 2001). As opposed to an empirical relation, the method applied here is based on the 3-D porous media reconstruction by conditional sequential indicator simulation (SIS presented by Deutsch and Journel 1998) from statistical parameters of 2-D images of thin sections. Since binary 3-D porous media reconstruction is performed, a binary indicator function based algorithm is more appropriate than truncated continuous Gaussian fields. Spatial statistical parameters of the binary image such as porosity and autocorrelation function are estimated from the binary image of the thin section. The variogram quantifies the dissimilarity of data in spatial distribution, as opposed to the autocorrelation function that reflects similarity. The variogram is computed using the following equation:
\[
\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [f(q_i) - f(q_i + h)]^2
\]

(3)

where \(N(h)\) is the number of pairs of data locations spaced a distance of \(h\) apart. The variogram of the image is related to the autocorrelation function \(A(h)\) as follows:

\[
\gamma(h) = A(0) - A(h)
\]

(4)

To ensure positive-definiteness of the variogram the experimental variogram of the image is then reproduced by an exponential function:

\[
\gamma(h) = c \left\{1 - \exp\left(-\frac{3h}{a}\right)\right\}
\]

(5)

where \(a\) is the range and \(c\) is the sill of the variogram. The range and sill are obtained by least-squares fit to the experimental variogram.

Based on the computed variogram model shown in Figure 2.10, multiple realizations of 3-D porous media were simulated using SIS conditioned to the thin section image. Since the photomicrograph is characterized by an indicator random function, \(f(q)\), an indicator-based simulation algorithm is most suitable. In the SIS algorithm, all the nodes in the 3-D grid are visited along a random path. At each node, a local conditional cumulative distribution function (ccdf) for \(f(q)\) is computed. This ccdf is conditioned to the 2-D image as well as to all previously simulated nodes along the random path. The ccdf is obtained by indicator kriging. First, a value for \(f(q)\) is drawn from the local ccdf. Next, this value is preserved as conditioning data and the algorithm proceeds to the next node along the random path. Finally, when all the nodes are visited, one realization of the 3-D binary field with the correct spatial statistics is generated. Figure 2.11 shows an example of a simulated 3-D porous medium.
The Lattice-Boltzmann (LB) method

The stochastically simulated 3-D porous media are geometrically complex. This poses challenges for the flow simulation technique. The LB method for numerical flow simulation is an appropriate choice, since the complex pore geometry is treated without any modifications or simplifications (Ladd 1994; Spaid and Phelan 1997; Bosl et al. 1998; Cancelliere et al. 1998; Keehm et al. 2001). The LB method is a discrete computational method based upon the Boltzmann equation that considers a typical
volume element of fluid to be composed of a large number of particles, represented by a particle velocity distribution function for each fluid component at each grid point following simple local rules (Doolen 1990). The time is counted in given time steps and the fluid particles can collide with each other as they move, possibly under applied forces. Since the local velocity fields may introduce inaccuracy (Manwart et al. 2002) the rules governing the collisions are designed such that the time-average motion of the particles is consistent with the Navier-Stokes equation at a macroscopic scale (Ladd 1994). The flow simulation is performed with pressure gradient ($\nabla P$) assigned across opposite faces of the 3-D cube. Next, a volume-averaged flux $\langle Q \rangle$ is computed from the local flux. Then, the macroscopic permeability ($k$) is calculated using the following equation:

$$ k = \frac{\langle Q \rangle}{\nabla P} \mu $$

where $\mu$ is the dynamic viscosity of the fluid. In order to capture the statistical variability, multiple realizations of 3-D porous media from each thin section were generated. The final permeability value for the photomicrographs was calculated by averaging these permeability estimates.

Figure 2.12 shows results of permeability and porosity estimation for 11 samples of deformed host rock. Porosity values range from 13.8 to 25.4 % as a result of varying degrees of compaction and grain size distribution. Grain contact type varies in images as a function of strain. Images (a) and (c) contain grains in concavo-convex (long) contact with relatively low porosity values, whereas the image (b) shows grains in point contact. Accordingly, permeability values range from 219 mD to 905 mD. Furthermore, poor sorting as observed in the image (d) reduces permeability compared to the image (b).
Figure 2.12. Permeability and porosity data for 11 samples of deformed host rock and 4 selected corresponding photomicrographs. Note grain contact types in photomicrographs and sorting in the image (d). Images (a and c) contain grains in concavo-convex contact with relatively low porosity values. Linear fit.
Figure 2.13 shows results of permeability and porosity estimation for five aforementioned faults and host rock as a function of slip for 70 samples. Average permeability for host rock is about 400 mD with a corresponding average porosity value of 20%. The wide variability of porosity and permeability values for both host and deformed rock is related to the natural heterogeneity present in the Aztec Sandstone. Another potential factor that contributed to the spread of data is the intrinsic variability between thin section images that correspond to the same rock domain.

Figure 2.13. Porosity (a) and permeability (b) data for 70 samples of host and deformed rock from 5 fault zones as a function of slip.

Figure 2.14 shows results of average permeability values of the fault rock for 66 samples (values are given in Table 2.1 at the end of this chapter) from 5 fault zones as a function of slip. Permeability values range from 24.4 mD in a fault with 2 km of apparent slip to 215 mD in a fault with 6 m of slip. Permeability computation was performed using images with at least 5% porosity as a lower limit for reliable permeability estimation, therefore the estimated fault rock permeability plausibly represents an upper limit of values. Previous studies conducted by Antonellini and Aydin (1994) documented low fault rock permeability values in eolian sandstones of Utah, specifically in the areas of the fault rock adjacent to the well developed slip surface (<0.1 mD). Two images (a and b) show effect of sorting and grain size on permeability. Porosity estimated from the image (a) is 13.1% and corresponding permeability is 159 mD. In the image (b), with 11.1% porosity, permeability is reduced by an order of magnitude (16.7 mD) compared to the permeability from the image (a).
Figure 2.14. Permeability (average by fault) data for 66 samples of fault rock and 2 selected corresponding photomicrographs from 5 fault zones as a function of slip. Porosity values in images differ by 2 %, whereas permeability varies by an order of magnitude. Power law fit.

Permeability estimation for the slip band shown in Figure 2.15 was performed on a portion of the thin section image. The red box shown on the slip band in the image (a) was used to compute permeability solely within the slip band. For this particular image, the corresponding permeability value is 9.7 mD with porosity value of 8.1 %. Even though permeability of the slip band is lower than in the fault rock, this value represents slip band permeability corresponding to one particular degree of infill by the hematite-
rich cement. In some cases, however, cement occupies more pores than in the image shown in Figure 2.15, thus reducing permeability to an even lower value.

**Figure 2.15.** Slip band photomicrograph (a) and portion of the slip band (b) that was used in permeability and porosity estimation. Pore space within the slip band is partially lost to the hematite-rich cement marked in image by brownish color.

**Effect of hematite grain coating on permeability**

Generally, eolian sandstones contain hematite grain coatings on detrital quartz grains (Chan et al. 2000; Eichhubl et al. 2004; Beiter et al. 2005). The thickness of hematite coating varies according to the diagenetic history of the sandstone. Hematite coating thickness variation up to 10 µm within host rock in 5 fault zones of the Aztec Sandstone is documented. In order to evaluate the effect of coating on permeability, the Kozeny-Carmen relation for the simple cubic packing of spheres (Figure 2.16) is used. Assuming that the flow rate \( Q \) through the cubic pack is equivalent to the flow along the cylindrical pipe with effective radius \( R_{eff} \) (denoted by the dashed circle in Figure 2.16) and quantified below:

\[
Q = -k \frac{A_p}{\mu} \frac{\Delta P}{\Delta L} = -\frac{\pi R_{eff}^4}{8\mu} \frac{\Delta P}{\Delta L}
\]

which gives

\[
k = \frac{\pi R_{eff}^4}{8A_p}
\]

(7)

where \( A_p \) is the surface area of the pore between four grains given by:

\[
A_p = 4R_g^2 - \pi R_g^2
\]

(8)
where $R_g$ is the radius of the grain. Assuming that the effective pore area is defined as follows

$$A_{\text{eff}} = \pi R_{\text{eff}}^2$$

and that the effective pore area is equal to the pore area

$$A_{\text{eff}} = A_p$$

the effective radius of the pore is defined as follows

$$\pi R_{\text{eff}}^2 = A_{\text{eff}} = 4R_g^2 - \pi R_g^2$$

which gives

$$R_{\text{eff}} = \left( \frac{4R_g^2 - \pi R_g^2}{\pi} \right)^{1/2}$$  \hspace{1cm} (9)

**Figure 2.16.** Hematite grain coating (in red) applied to the cubic packing of grains, resulting in the reduction of the cross-sectional area, and hence, permeability.

1 µm, 2 µm and 10 µm of hematite coating thicknesses are used based on lowest observable values in photomicrographs. Hematite thickness values used here are consistent with those observed in eolian sandstones of the Colorado Plateau (Chan et al. 2000; Eichhubl et al. 2004; Beitler et al. 2005). As hematite coating is applied to the grain, the effective radius of the pore $R_{\text{eff}}$ is reduced by amount $L$. In this model, grain
point contacts remain intact with no hematite coating applied, thus, the grain geometry is conserved. This assumption appears to be reasonable, as it is of interest to compute permeability as a function of grain size in relation to the effective area of the pore channel. This gives

\[ R'_{\text{eff}} = R_{\text{eff}} - L \]  \hspace{1cm} (9)

The results of permeability variation as a function of grain size are shown in Figure 2.17. The application of hematite coating with 1 and 2 µm thickness reduces permeability by up to 13 % at the average grain size (about 0.2 mm) documented in the Aztec Sandstone, whereas 10 µm thick coating reduces permeability by about 55 %. Furthermore, the use of the cubic packing of spheres yields the largest pore area (hence the effective radius of the pore) between grains, and therefore, might underestimate the degree of the permeability reduction.

**Figure 2.17.** Permeability value for unstained cubic packing of spheres (in blue). Permeability reduction (normalized by the permeability values of unstained cubic packing of spheres) as a function of grain size with 1, 2 and 10 µm hematite coating thickness, respectively (in green).
Discussion

The results of the porosity estimation from thin section images of the Aztec Sandstone reveal the importance of the appropriate treatment of images prior to the estimation of porosity. Direct grayscale thresholding, or thresholding of various color planes of the original RGB image introduced artifacts and an unacceptably wide range of porosity estimates (from 9 to 31 %). In contrast, removal of thresholded ‘xenopixels’ proved to be a successful procedure and yielded reasonable values of porosity (18.7 %). Statistically supervised classification of image domains such as pores and grains into distinct groups is another effective method of porosity estimation (17.7 %). This study demonstrated methodologies for accurate porosity estimation and reduction of associated uncertainty. Treatment of images and morphological operations performed on binary versions of the original images reduced porosity variation from 9-31 % to 17.7-18.7 % and eliminated artifacts.

Grain size distribution based on the numerical sieving procedure is a powerful non-destructive method that only requires a thin section image, which is relatively inexpensive and fast to obtain. The wide range of grain size distribution in two deformed host rock samples is due to the grain size variation between images and sorting within individual photomicrographs.

Analysis of values for both host and deformed host rock show wide ranges of porosity and permeability values. Permeability values for host rock lie in the range from 200 to 1100 mD. Corresponding porosity values range from 15 to 25 % averaging 20 %. The deformed host rock values of permeabilities range from 10 to 800 mD. Porosities within deformed host rock are slightly lower than in an undeformed host rock with an average value of 16 %. Average permeability values of the fault rock vary over an order of magnitude (from 16.7 to 159 mD) as a function of slip. Porosity, by contrast, does not show strong correlation with the amount of slip. This may be related to the inhomogeneity within fault rock as a result of the cataclasis and relatively little deformed blocks of the host rock preserved within the fault core. Although, grain size is reduced, porosity values do not show a strong decreasing trend. Slip band porosity (8.1 %) is slightly lower than that of the fault rock. This is a result of the presence of pore-filling hematite-rich cement.
In this study, all the thin sections were processed in a consistent, operator-bias free manner. Therefore, it is believed that the spread in the permeability and porosity values comes from the natural heterogeneity, as well as the stochastic variability in the geostatistical reconstruction of the 3-D volume from the 2-D thin sections. In this study, as in any 3-D reconstruction study based on 2-D data, representative elementary volume is of a great importance. Similar issues of representativeness may also arise in conventional laboratory measurements on core plugs.

Conclusions

Laboratory estimation of the petrophysical properties of thin slip bands and other fault rock materials can be a challenge. This study demonstrates how reliable and inexpensive porosity and permeability estimates can be accomplished via a computational rock physics approach based on thin section image analyses, followed by application of Lattice-Boltzmann flow simulation. The results of the petrophysical characterization of the fault zone components can then be used in the permeability upscaling of fault zone blocks (discussed in Chapter 3).

The following main conclusions can be drawn from this study:

1. A technique for the computation of porosities based on the photomicrographs was developed and applied to the undeformed host rock, deformed host rock and fault rock in the Aztec Sandstone in the Valley of Fire State Park, Nevada. The methodology incorporates image treatment using morphological operations on grain boundaries. As a result, artifacts introduced during various image conversions including thresholding of different color planes were successfully removed, thus providing more accurate results of porosity estimation.

2. A method for determining grain size distribution was applied to the images with varying grain sizes and sorting. The technique is a non-destructive, fast and inexpensive numerical alternative to more conventional laboratory methods.

3. 3-D reconstruction of porous media based on the statistical modeling of 2-D thin section images was applied to the set of photomicrographs. Lattice-Boltzmann flow simulation produced permeability estimates for sections with varying degree
of geologic features. This technique is an alternative to more conventional laboratory and in-situ permeability measurements.

Acknowledgements

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Notation

\( A \) cross-sectional area
\( a \) range of variogram
\( C \) autocorrelation function
\( c \) sill of variogram
\( ccdf \) conditional cumulative distribution function
\( f(q) \) indicator function
\( h \) distance between data locations
\( k \) macroscopic permeability
\( L \) hematite coating thickness
\( \mu \) viscosity
\( N(h) \) number of pairs of data locations
\( \nabla P \) pressure gradient
\( \langle Q \rangle \) volume-averaged flux
\( T \) digitized photomicrograph matrix

References for chapter 2


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<td>fr</td>
<td>8.5</td>
<td>26.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fr</td>
<td>13.2</td>
<td>14.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 2.1 (cont-d).* Porosity, permeability, hematite cement and feldspar content for 5 fault zones and host rock in the vicinity of the fault zones. hr – host rock; dhr – deformed host rock; fr – fault rock.
Chapter 3
Permeability upscaling of fault zones in the Aztec Sandstone, Valley of Fire State Park, Nevada

Abstract

We evaluate the effect of open and filled slip surfaces on the upscaled permeability of two fault zones with 6 and 14 m strike-slip in an eolian sandstone in the Valley of Fire State Park, Nevada. Each fault zone is composed of several fault components: a fault core, bounded by filled through-going slip surfaces referred to as slip bands, and a damage zone that contains joints, sheared joints and deformation bands. We focus on the slip bands and characterize their geometry, composition, and petrophysical properties. Measurements and modeling show that slip band permeabilities can vary over 12 orders of magnitude depending on the degree of fill within the slip bands. The slip bands along with other fault zone components are represented in finite volume numerical calculations in order to test the impact of various slip band representations on upscaled fault zone permeability. Unstructured triangular grids are used in these computations to resolve accurately the geometry of the fault zone features. The results show that the upscaled permeability of the faults can vary significantly as a function of slip band permeability. Specifically, we observe 2 orders of magnitude variation in upscaled fault zone permeability in the fault-normal direction and a factor of 2 variation in the fault-parallel direction. In addition, the numerical results presented here are compared to the earlier numerical results of Jourde et al. (2002) who used structured Cartesian grids for the numerical simulations. The results obtained here are in qualitative agreement with these earlier calculations but use about a factor of 250-400 fewer numerical cells.

Introduction

Extreme values of permeability often have a dominant effect on fluid flow. In deformed rocks, faults may represent the extreme values in permeability and as a result impact the management of groundwater aquifers and petroleum reservoirs (NRC committee 1996). However, the hydraulic properties of faults are in general complex: faults may display a variety of flow behaviors, acting as conduits, barriers or combined...
conduit-barrier systems (Smith et al. 1990; Scholz, 1990; Antonellini and Aydin 1994; Caine et al. 1996; Caine and Forster 1999; Aydin 2000). Therefore, it is of prime importance to characterize fault zone permeability in a geologically realistic manner in order to represent faults in subsurface fluid flow simulations. Of particular interest are the faults in eolian sandstones, which are known to form giant aquifers such as the Nubian Sandstone in the Sinai Peninsula (Abd El Samie and Sadek 2001), the Navajo-Nugget aquifer in the western United States (Heilweil and Freethy 1992), the Mercosul aquifer system in South America (Araujo et al. 1999) and petroleum reservoirs (Zamora Valcarce et al. 2006).

Idealized representations of fault architecture in eolian sandstones often include fault core composed of low-permeability fault rock, high-permeability slip surfaces, and a surrounding damage zone (Figure 3.1).

**Figure 3.1.** Conceptual model for upscaling of fault zone permeability in sandstone (modified from Antonellini and Aydin 1994, Caine et al., 1996 and Jourde et al., 2002). (A) Localized map of fault zone geometry. (B) Two-dimensional permeability tensor ellipse with maximum permeability ($k_p$) for fault-parallel flow and minimum ($k_n$) for fault-normal flow.

In such scenarios, the fault rock extent and permeability are crucial for determining the fault-perpendicular flow component. Slip surfaces, which are the most continuous structural element, often control the fault-parallel flow and are commonly treated as two planar surfaces separated by a constant overall aperture. In contrast to this idealized representation, however, our recent field observations (noted below and described in Chapter 1 of this dissertation) reveal that a majority of the slip surfaces within the fault zones in the Aztec Sandstone are characterized by infill (of a reddish/orange/maroon color) with a small thickness on the order of one millimeter, a typical value of slip
surface aperture. This indicates that these slip surfaces are not parallel plates separated by a small aperture but may rather act as low-permeability slip bands. In this study, we investigate the nature of these slip bands and assess their impact on equivalent fault zone permeabilities.

Permeability upscaling procedures seek to determine “equivalent” or “upscaled” permeabilities which, for specified boundary conditions, provide the same flow rate as the corresponding fine-scale (detailed) model. In practical settings, permeability upscaling procedures can be classified as either analytical or numerical techniques (Wen and Gomez-Hernandez 1996; Renard and de Marsily 1997). An analytical approach was used by Antonellini and Aydin (1994) and Shipton et al. (2002) in their studies involving the determination of upscaled fault zone permeability.

In recent years, computational advances made it possible to employ numerical methods for the upscaling of detailed permeability fields. Typically, the method proceeds by solving the single-phase steady-state flow equations over the fine-scale region of interest and computing the upscaled permeability from the integrated fine-scale flow rates. Boundary conditions must be specified for these flow solutions. For a square domain in an x-y system, the most commonly used procedure entails the specification of constant pressure on x-oriented faces and no-flow on y-oriented faces. This solution provides the x-component of the upscaled permeability (assuming x is aligned with a principal direction of the full equivalent permeability tensor). An analogous solution with flow in the y direction provides the y-component of the upscaled permeability. This type of method was recently used in a number of studies of fault zones; see, e.g., Caine and Forster (1999), Flodin et al. (2001), and Jourde et al. (2002).

One of the main advantages of this technique is the ability to assess the role of small-scale features on the upscaled fault zone permeability. The importance of relatively small-scale features was addressed in a previous study by Durlofsky (1992), who showed possible reduction of protolith (eolian sandstone) permeability by an order of magnitude as a result of the variation of cross-bedding permeability. In other studies (Matthäi et al. 1998; Taylor et al. 1999), it was shown that flow attributed to the joints can increase upscaled permeability by two orders of magnitude. The effect of deformation bands on upscaled permeability was discussed by Antonellini and Aydin (1994), Matthäi et al.
(1998), Taylor and Pollard (2000) and Sternlof et al. (2004), who documented relative reduction in upscaled permeability by 1-3 orders of magnitude. In this work, we apply a finite volume numerical method with imposed pressure-no flow boundary conditions for the computation of the upscaled fault zone permeability, with a particular focus on the impact of slip surface and slip band permeabilities on the resulting equivalent permeability.

**Geologic Setting of Aztec Sandstone**

Strike-slip faults within the Aztec Sandstone are exceptionally well exposed in the Valley of Fire State Park, located in the North Muddy Mountains of Southern Nevada 60 km NE of Las Vegas (Figure 3.2). The Aztec Sandstone was deposited in a back arc basin from late Triassic to Middle Jurassic period (Bohannon 1983; Marzolf 1983). The Aztec Sandstone is laterally correlated with the Navajo Sandstone exposed in Utah (Blakey 1989). The stratigraphic thickness of the Aztec Sandstone exposed in the Valley of Fire is up to 1400 m (Bohannon 1983; Marzolf 1983, 1990). Texturally, it is a well-sorted quartz arenite with average grain size of 0.25 mm, porosity values ranging between 15-25% and permeabilities from 100 to 5900 mD (Antonellini and Aydin 1994; Flodin et al. 2004).

Two main fault sets with opposite sense of shear were developed in the Valley of Fire. Both fault sets, a right-lateral set of faults oriented SE-NW and a left-lateral set that strikes S-N, crosscut each other. Strike-slip faulting postdates extensive formation of deformation bands associated with the Cretaceous Sevier Orogeny that predates jointing (Myers and Aydin 2004). The evolution of the faults by shearing along existing arrays of echelon joints was described by Myers and Aydin (2004).
The faults studied in this article are left-lateral and were chosen from en echelon fault systems consisting of steeply dipping joint arrays. The joint arrays were sheared to form a new generation of joints. As a result, the fault zone formed by this mechanism is
composed of sheared joints, splay fractures and fault rock. Consequently, splay fractures are subjected to shear resulting in the formation of newer generations of splay fractures. This process is hierarchical and continuous throughout several stages of fracturing. During this process, the fault core and surrounding damage zone expand. The core contains and is bounded by slip surfaces and is surrounded by the fault damage zone. Most of the structural elements within the fault zone are subvertical (Myers 1999). We therefore consider two-dimensional representation of the fault zone in our permeability upscaling computations.

**Description of the slip bands**

As indicated above, many previous fluid flow studies represented slip surfaces as parallel plates with a distinct aperture value (Jourde *et al.* 2002; Flodin *et al.* 2004). As a result, these models predict enhanced fault-parallel flow. As we now describe, our most recent observations and laboratory analyses showed that slip surfaces cannot always be represented by two distinct planes with a given aperture. Specifically, as a result of diagenetic alteration, we observed slip surfaces with varying degrees of mineral infill. Consequently, the petrophysical properties of slip surfaces, such as porosity, permeability and connectivity, do not remain constant throughout the fault evolution.

Generally, most of the slip surfaces are tabular zones of varying degrees of infill bounded by two planes. For this reason these features are more appropriately referred to as slip bands. Slip band lengths range from several centimeters to several tens of meters, while their widths range from 0.1 to 1 mm. Slip bands form as single features, but may evolve into a set of slip bands (Figure 3.4.B). Slip band density may vary dramatically along a single fault reaching its maximum value within the widest zones of well-developed fault rock. Slip band densities of well-developed zones can exceed 10 per 10 cm in both fault-parallel and fault-perpendicular directions. The hierarchical evolution of slip band networks within the fault with 14 m left-lateral slip is shown in Figure 3.3. The first generation slip bands were sheared in a left-lateral sense to form second generation slip bands, which were later sheared in a right lateral sense to form third generation slip bands etc. A similar mechanism for fault development by sheared joints is documented by Myers and Aydin (2004) and Flodin and Aydin (2004).
Figure 3.3. Hierarchical relationship between 5 generations of slip bands within the core of the fault with 14 m left lateral slip. (A) Map by Nickolas Davatzes. (B) Photograph and (C) schematic representation of a portion of the fault core and slip bands. Pencil on photograph is 125 mm long.

The most extreme degrees of infill were observed in slip bands partially filled by whitish cement (Figure 3.4.A) and reddish-maroon mineral cement (Figure 3.4.B). Slip bands containing whitish infill are not easily identifiable in-situ. Twenty two hand specimens were collected from 5 left-lateral faults with maximum offsets ranging from 6 m to 2 km out of which 31 thin sections were prepared. Thin sections were polished and blue epoxy impregnated under vacuum in order to better characterize pore space. Thin sections were cut in two orthogonal directions, parallel and perpendicular to the fault strikes. Sections were analyzed using an optical microscope with a digital camera attachment. Several hundred high resolution (1520×1080) photomicrographs were obtained and processed.
In order to analyze the mineralogical content of slip band infill, Scanning Electron Microscopy (SEM) distance traverse point count data corresponding to Si, O$_2$ and Fe rich minerals were obtained (Figure 3.5). Counts were sampled along three transects perpendicular to two different slip bands of the fault core for the fault with 14 m slip. Analyses showed strong peaks in Fe-rich mineral cement (goethite/hematite mixture) and a corresponding decrease in Si and O$_2$ rich mineral cement. Similarly, Eichhubl et al. (2004) documented iron-rich infill in undeformed parts of the Aztec Sandstone. Widespread occurrence of hematite grain coatings on detrital quartz grains within eolian sandstones of the Colorado Plateau was documented by Chan et al. (2000) and Beitler et al. (2005). X-Ray Diffraction (XRD) analysis by Eichhubl et al. (2004) showed the widespread occurrence of predominantly goethite and hematite. The XRD analyses performed on the sample corresponding to the whitish infill showed a strong peak corresponding to amorphous silica believed to be opal (personal comm. D. Lowe, Stanford University, 2005). The matrix supported nature of the cement within the slip bands (Figure 3.4.B) and the origin of the fluids responsible for the precipitation of the cement are currently under investigation.
Figure 3.5. Backscatter secondary electron image of two slip bands (oriented vertically on A and B) within the core of the fault with 14 m left lateral slip and corresponding response (shown on A’ and B’) to Fe, Si and O₂ rich elements present along the transects (denoted by yellow area). Note strong peak of hematite/goethite (increase in Fe) infill along both transect and relative reduction in Si and O₂.

**Computation of slip band permeability**

Opal as well as goethite/hematite infill markedly reduce porosity, and hence permeability of slip bands. Therefore, it is essential to represent the highly variable nature of slip bands in the computation of equivalent fault zone permeabilities. Moreover, the presence of open-mode fractures that occur at high angles to slip bands (Figure 3.6) further complicates fluid flow across slip bands. Open fractures were observed in a majority of slip bands examined in our study. The presence of hematite and goethite remnants on the walls of these cracks eliminates the possibility of their artificial initiation (which could occur during sample collection or thin section preparation).
Figure 3.6. Photomicrograph of slip band (orthogonal to the longest axes of photomicrograph) with hematite/goethite infill (shown in brown) (A), binary image of the portion of the slip band that contains through-going open or partially open crack (B), schematic representation of the open crack in permeability computation procedure (C). Epoxy resin (pores) is denoted by blue color on photomicrograph (A) and by white color on binary image (B). Photomicrograph is in the cross polarized view.

We have considered three main cases of slip band texture variation based on the field and laboratory observations. These correspond to (1) open slip surfaces, (2) slip bands filled with varying degrees of cement and (3) filled slip bands with varying densities of cross-cutting open mode fractures. In order to use realistic values of slip band permeability in our fault zone models, appropriate computation techniques were employed to determine the range of slip band permeability for each of these cases.

Permeability values of slip bands partially filled by hematite/goethite cement (Figure 3.4.B) were computed using thin-section image analysis in conjunction with a computational rock physics-based algorithm called PETS (permeability estimation from thin sections). Image analysis techniques have proven to be powerful, fast and non-destructive for various applications (Antonellini et al. 1994, Ahmadov et al. in prep.). PETS (Keehm 2003) requires an input file (photomicrograph) in which pore space is differentiated from grains, and 3D pore space is reconstructed from a 2D statistical correlation between pores and grains based on variogram modeling. Finally, permeability is computed using the Lattice-Boltzmann method (Keehm et al. 2004). This method estimates permeability more accurately than empirical relationships such as the Kozeny-Carmen equation and is less sensitive to the discrepancy between thin sections and rock samples. However, this method has limitations imposed by variogram modeling, which are related to the pore structure of the photomicrograph and to the minimum porosity value (personal comm. Y. Keehm 2005). Therefore, permeability was computed using
this method only for slip bands with porosity values greater than 5%. Results showed variations in slip band permeability ranging from 2.8 to 150 mD.

Permeability values of unfilled or partially filled (by opal cement) slip bands (Figure 3.4.A) were computed using a parallel plate model. This technique, employed previously by Matthai et al. (1998), Taylor et al. (1999) and Jourde et al. (2002), is appropriate when it is reasonable to assume that fractures are completely open or contain elongated pores (slip surfaces or joints). The permeability $k_f$ for a fracture of aperture $a$ is given by:

$$
k_f = \frac{a^2}{12}
$$

The average slip band aperture observed in thin sections is 0.25 mm. Using a parallel plate model with this aperture value yields a permeability value of about $5 \times 10^3$ D for a representative slip band. However, in the subsurface, apertures may vary due to the variations in the stress normal to the slip bands and fluid pressure throughout the evolution of fault zones. Therefore, we assume that this value is the maximum slip band permeability in our permeability upscaling procedure.

Permeability values of filled slip bands that contain cross-cutting open mode fractures (Figures 3.6.A, 36.B) were computed using the modified parallel plate model (for the cross-cutting fractures) in conjunction with a layered media model (Figure 3.6.C). The permeability in the direction normal to the slip band is then given by:

$$
k_x^* = \frac{1}{L} \left[ a \frac{k_f}{\tau} + (L-a)k_m \right]
$$

where $k_x^*$ is an effective (normal) permeability of the slip band, $L$ is the length of the slip band, $a$ the aperture of the open mode fracture, $k_f=\frac{a^2}{12}$ is the permeability of the cross-cutting open mode fracture, $k_m$ is the permeability of the matrix within the slip band, and $\tau$ is the tortuosity of open mode fracture (defined as the total arc length of the fracture divided by the slip band thickness $W$ – see Figure 3.6.C). If the number of open mode fractures cutting across the slip band is $n$, then

$$
k_x^* = \frac{1}{L} \left[ na \frac{k_f}{\tau} + (L-na)k_m \right]
$$
Most slip bands that contain cross-cutting open mode fractures are filled by hematite/goethite cement, which reduces porosity markedly. Therefore, flow across the slip bands is localized along these fractures and the assumption of impermeable matrix within the band \((k_m = 0)\) is reasonable. The aperture of open mode fractures was observed to vary between 1 and 5 \(\mu m\). The permeability of these fractures (computed from equation 1) will therefore vary between 84 and \(2.1 \times 10^3\) mD. The average measured tortuosity of the fractures was 1.15. Finally, the number of fractures per slip band varies significantly. The optical microscopy analyses of slip bands showed a maximum density of 10 fractures per 23 mm (sample height on standard thin section slide) portion of slip band. Thus, this density value was used as a maximum number of fractures \((n)\) in equation 3. However, in many slip bands fractures are not present or have much lower densities. In view of this, the minimum permeability slip band was taken to be that of a 10 m long slip band with just one cross-cutting fracture of aperture 1 \(\mu m\).

Based on the values given above, slip band permeabilities were calculated to be in the range of \(7 \times 10^{-6}\) mD to 3.9 mD. As mentioned earlier, partially filled slip band permeabilities ranged from 2.8 mD to 150 mD, while open slip surfaces give permeabilities as large as \(5 \times 10^6\) mD. In the computations of equivalent fault zone permeability presented below, we will therefore vary slip band permeability from \(7 \times 10^{-6}\) mD to \(5 \times 10^6\) mD.

**Fault zone permeability upscaling**

An efficient unstructured discrete fracture model is used to compute the effective properties of the fault zone. The method employs a finite volume numerical technique described in detail by Karimi-Fard *et al.* (2004) and Sternlof *et al.* (2006). The advantage of this model over the standard Cartesian approach lies in its ability to capture accurately the geometry of all discrete structural features (joints, sheared joints, deformation and slip bands) without using a large number of cells. The method requires the use of a sophisticated grid generation technique that is able to resolve the complex fault zone geometry. In this work we apply the method of Shewchuk (1996) for the generation of the triangular grid, who used Ruppert’s Delaunay refinement algorithm to generate
guaranteed-quality meshes (having no small angles). We represent small-scale linear features such as slip surfaces and joints using computational cells that are of the same thickness as the feature, which means that these features are not resolved in the transverse (thin) direction by the grid. This reduces the overall number of cells and simplifies the gridding procedure.

The fault zone for the fault with 6 m slip and the corresponding grid are shown in Figure 3.7. This model is discretized using about 15,000 cells (the host and fault rock are represented by triangles and the structural features are represented by linear segments). The model of 14 m slip fault zone shown in Figure 8.B is discretized using about 10,430 cells. Jourde et al. (2002) considered the same model using a Cartesian grid approach. In their work, a uniform $2,000 \times 2,000$ grid (for a total of 4,000,000 cells) was applied to capture all of the fault zone details. In the current work (as in the earlier work of Jourde et al. 2002), we use the maps developed by Myers (1999) to provide the detailed geometric fault zone description required as input to the model.

![Figure 3.7](image)

**Figure 3.7.** A. 6 by 6 m block from a strike-slip fault with 6 m of slip (modified by Jourde et al. 2002 from Myers 1999). B. Corresponding discretization of fault components representation in permeability upscaling model. Fault zone components as indicated on the right.

We are interested in computing the equivalent permeability in the two principal directions ($x$ and $y$), which provide fault-normal ($k_n$) and fault-parallel ($k_p$) upscaled permeabilities. As discussed earlier, we impose constant pressure no-flow boundary conditions on the fine-scale domain and then compute a coarse-scale (upscaled) permeability that provides the same total flow rate $Q$ for the imposed pressure drop $\Delta p$. Two such problems are solved, with pressure drop prescribed in the $x$ and $y$ directions.
respectively. Then, given the prescribed pressure drops ($\Delta p_x$ and $\Delta p_y$) and the resulting flow rates ($Q_x$ and $Q_y$), the equivalent permeability components can be computed as follows:

$$k^*_x = \frac{Q_x L_x}{L \Delta p_x}, \quad k^*_y = \frac{Q_y L_y}{L \Delta p_y},$$

where $L_x$ and $L_y$ represent the physical dimensions of the model.

Fault-parallel and fault-normal permeabilities of two fault blocks of 6 by 6 m (covering an area of 36 m$^2$) were computed (Figure 3.8). Slip bands are the most continuous features on the maps. In previous work slip surfaces were assigned permeability values of $5 \times 10^6$ mD. This value was used for both joints and slip surfaces based on the parallel plate model described by Nelson and Handin (1977), which directly correlates fracture aperture to fracture permeability.

![Figure 3.8](image)

Figure 3.8. Two fault zone blocks used in upscaling of permeability with 6 (map A) and 14 m (map B) of slip, respectively. Maps modified by Jourde et al. 2002 from Myers 1999.

However, as discussed above, our textural and mineralogical analyses and slip band permeability computations suggest a wide range of slip band permeabilities. We will therefore vary this quantity, though other permeability values will be specified (and fixed) based on field measurements. We use an isotropic matrix permeability of 200 mD, which represents a local mean value of Aztec Sandstone permeability documented by Myers (1999) and Flodin et al. (2005). The bedding plane does not show significant anisotropy so our use of isotropic matrix is reasonable (we note that the specification of
isotropic host rock is consistent with earlier work of Flodin et al. 2001 and Jourde et al. 2002).

Antonellini and Aydin (1994) used a field minipermeameter to measure the permeability of deformation bands. Their results showed an average of 3 orders of magnitude reduction in deformation band permeability compared to host rock permeability. Myers (1999) documented similar permeability values for both sheared joints and deformation bands using petrographic image analysis of thin sections and permeability computation based on the Kozeny-Carmen relationship. Jourde et al. (2002) used a permeability value of 0.1 mD for sheared joints and deformation bands. Thus, a permeability value of 0.1 mD was assigned to the sheared joints and deformation bands in this study. Myers (1999) also used direct laboratory measurements to determine the permeability of the fault rock material and found a 1-4 order of magnitude permeability reduction compared to host rock. Thus, in our calculations, fault rock was also assigned a permeability value of 0.1 mD. The joint permeability was calculated based on the parallel plate model (Matthai et al. 1998; Taylor et al. 1999) using equation 1. Jourde et al. (2002) used an aperture value of 0.25 mm for joints based on the field observations, which is the value applied here. The permeability values for all fault zone components used in the fault block permeability upscaling computations are summarized in Table 3.1.

<table>
<thead>
<tr>
<th>Fault component</th>
<th>$K$, mD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock</td>
<td>200</td>
</tr>
<tr>
<td>Fault rock</td>
<td>0.1</td>
</tr>
<tr>
<td>Sheared joint</td>
<td>0.1</td>
</tr>
<tr>
<td>Joint</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td>Slip band</td>
<td>$7 \times 10^{-6}$ - $5 \times 10^6$</td>
</tr>
</tbody>
</table>

Table 3.1. Permeability values of fault zone components used in fault block permeability upscaling

In order to represent the textural heterogeneity present within the slip bands and assess its impact on effective permeability of the system, a wide range of slip band permeability values were tested. Results for zones of faults with 6 m and 14 m of slip are presented in Figure 3.9. The results demonstrate that significant variation of slip band
permeability ($k_{sb}$) has only a small effect on the upscaled permeability in the fault-parallel direction for the fault zones considered. Upscaled permeability in the fault-normal direction, by contrast, varies by over 2 orders of magnitude over the range of $k_{sb}$ investigated. Although the results for $k_p$ show little variation with $k_{sb}$, it is important to note that joints as well as slip bands are through-going components present at the block size used for the calculations. Our knowledge of fault zone geometry suggests that the impact of slip bands on equivalent permeability will increase with increasing block size, as continuous joints will no longer be present throughout the block, while the through-going character of the slip bands is more likely to persist.

![Figure 3.9](image)

**Figure 3.9.** Effect of slip band permeability on upscaled fault block permeability of two faults with 6 (in red) and 14 m (in blue) of left-lateral slip, respectively.

The different behaviors observed in Figure 3.9 for $k_n$ and $k_p$ can be understood qualitatively by considering flow in layered systems. Fault-parallel flow is essentially along the layers while fault-normal flow is across the layers. When $k_{sb}$ is small, the impact of $k_{sb}$ on $k_p$ is small since flow will simply avoid the low-permeability slip bands (the equivalent permeability for flow along layers is the weighted arithmetic average). In
the case of $k_n$, however, because the slip bands are through-going, the flow cannot avoid the slip bands and their impact is large (the equivalent permeability for flow across layers is the weighted harmonic average). Once $k_{sb}$ is large, however, the situation is essentially the reverse. Now $k_n$ becomes insensitive to $k_{sb}$ (the slip bands offer no resistance) while $k_p$ becomes very sensitive. In fact, were we to increase $k_{sb}$ further (which would correspond to the case of unfilled slip bands with aperture larger than 0.25 mm), $k_p$ should scale with $(k_{sb})^3$. The critical values of $k_{sb}$ corresponding to the locations of the kinks in the $k_n$ and $k_p$ curves will, however, depend on the specific geometrical configuration of the fault zone components, their permeability values, and the scale of the fault blocks under consideration. This explains why these kinks appear at different values of $k_{sb}$ for the 6 m and 14 m slip faults, at least for $k_n$.

The results from this study were compared to those of Jourde et al. (2002) for the case of unfilled slip bands ($k_{sb}=5\times10^6$ md) for fault zones with 6 and 14 m of slip. Table 3.2 presents these comparisons for both $k_p$ and $k_n$. For fault-parallel flow, the values are in reasonably close agreement, with differences of 7% and 26% (relative to the results of Jourde et al.).

<table>
<thead>
<tr>
<th></th>
<th>Jourde et al. (2002)</th>
<th>This study</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault with 6 m slip</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_p$</td>
<td>1590 mD</td>
<td>1173 mD</td>
<td>-26%</td>
</tr>
<tr>
<td>$k_n$</td>
<td>4.4 mD</td>
<td>2.8 mD</td>
<td>-36%</td>
</tr>
<tr>
<td>Fault with 14 m slip</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_p$</td>
<td>1480 mD</td>
<td>1577 mD</td>
<td>+7%</td>
</tr>
<tr>
<td>$k_n$</td>
<td>44.3 mD</td>
<td>18.8 mD</td>
<td>-58%</td>
</tr>
</tbody>
</table>

Table 3.2. Comparison of permeability upscaling results with Jourde et al. (2002)

For the case of fault-normal flow we observe larger differences. However, given that we are here computing upscaled values for systems displaying complex geometry, very fine scale features and property variations of over 7 orders of magnitude, the agreement is still qualitatively reasonable. The observed differences in $k_p$ and $k_n$ are likely due to the differing numerical representations of the features with extreme permeability values. For example, the mapping of fine-scale features onto a Cartesian grid applied in the earlier study required the computation of grid block properties, and this can act to modify the
connectivity between features, which in turn may impact \( k_p \) and \( k_n \). In any event, further investigation will be required for a full understanding of the differences between the two methods.

Discussion

In this study, we analyzed the effect of varying slip band infill on the hydraulic properties of slip bands and on the upscaled permeabilities of fault zones in which the bands occur. Slip band permeabilities were determined using a set of computational rock physics-based numerical algorithms, with adjustments made for open cracks that may occur within the slip bands. Our results for two fault blocks illustrate quantitatively the importance of detailed characterization of fault zone components in evaluating the hydraulic behavior of faults.

Various degrees of slip band infill result in 10 orders of magnitude variation in slip band permeability values. This range of slip band permeabilities was then used to compute upscaled permeabilities of fault blocks. The results show 2 orders of magnitude variation of upscaled permeability in the fault-normal direction as a function of slip band permeability. Small values of slip band permeability dramatically impact upscaled fault zone permeability in the fault-normal direction. Once a critical value of slip band permeability is reached, further change in fault-normal upscaled permeability is essentially absent, indicating a critical point beyond which slip bands are no longer a barrier to fault-normal flow. For fault-parallel flow, by contrast, less than an order of magnitude variation in upscaled permeability was observed. At larger values of slip band permeability, however, the impact of slip band permeability on upscaled fault-normal permeability will be large. Although we have analyzed only two fault zone blocks, which both demonstrate differences in hydraulic behavior of fault zones as a function of slip band permeability, it is clear that the impact of small scale structural features (slip bands, joints) on the flow behavior of faults is complex but nonetheless systematic.

It is interesting to compare the current permeability upscaling results to those of Jourde et al. (2002). The unstructured finite volume method employed in this study accurately represents complex small-scale structural features and provided reasonable agreement with the earlier results of Jourde et al. (2002). The current method is much
more efficient computationally, requiring only about 15,000 cells in comparison to the 4,000,000 cells used by Jourde et al. who computed upscaled permeabilities using structured Cartesian grids. A full assessment of the quantitative differences between the two sets of results will require further study.

Conclusions

Our study of permeability upscaling of fault zones in the Aztec Sandstone has shown a significant variation in the hydraulic behavior of faults depending on the value of slip band permeability. The following specific conclusions can be drawn from this study:

4. Field observations and laboratory analyses reveal the complicated nature of slip bands and show traces of diagenetic processes present within the fault zone, resulting in dissolution and precipitation of silica and the subsequent alteration of slip band permeability. Scanning electron microscopy of the slip band infill shows a relative increase of iron rich minerals and a decrease of oxygen and silica rich minerals. The matrix supported nature of material present within the slip bands suggests fluid-based transport of infill.

5. The results demonstrate the variation of the upscaled fault zone permeability as a function of slip band permeability. The upscaled permeability in the fault-normal direction shows 2 orders of magnitude variation as a function of the slip band permeability. The upscaled fault-parallel permeability, by contrast, is much less sensitive to variations in slip band permeability over the range considered.

6. Results using the unstructured finite volume technique applied here were compared with results from a previous fault zone upscaling study (Jourde et al. 2002) in which a Cartesian grid representation was applied. Numerical results from the two procedures are in reasonable agreement, though quantitative differences are observed in some cases. The current method is much more efficient computationally, though it does require the use of sophisticated unstructured gridding procedures.

7. The method introduced here is not case specific and can be applied to other types of structural heterogeneities including faults, joints and deformation bands with
any geometric configuration. The resulting upscaled models can be used for simulating flow in large-scale aquifers and reservoirs.

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**Notation**

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\begin{align*}
K & \quad \text{general permeability} \\
K^*_x & \quad \text{effective permeability in } x\text{-direction} \\
a & \quad \text{fracture aperture} \\
\tau & \quad \text{tortuosity of fracture} \\
k_f & \quad \text{fracture permeability} \\
k_m & \quad \text{matrix permeability} \\
n & \quad \text{number of fractures per domain} \\
Q_x & \quad \text{flow rate in } x\text{-direction} \\
Q_y & \quad \text{flow rate in } y\text{-direction} \\
L_x & \quad \text{dimension of the model in } x\text{-direction} \\
L_y & \quad \text{dimension of the model in } y\text{-direction} \\
\Delta p_x & \quad \text{pressure drop in } x\text{-direction} \\
\Delta p_y & \quad \text{pressure drop in } y\text{-direction} \\
k_{sb} & \quad \text{slip band permeability} \\
k_n & \quad \text{fault-normal upscaled permeability} \\
k_p & \quad \text{fault-parallel upscaled permeability}
\end{align*}
\]
References for chapter 3


