FINAL REPORT

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Title: Structural Heterogeneities and Paleo Fluid Flow in an Analog Sandstone Reservoir

Principal Investigators:

Dr. David D. Pollard (650-723-4679; Fax 650-725-0979; dpollard@stanford.edu)
Dr. Atilla Aydin (650-725-8708; Fax 650-725-0979; aydin@stanford.edu)
Department of Geological and Environmental Sciences
Stanford University
Stanford, CA 94305-2115

Project Scope and Objectives:
We developed conceptual and quantitative mechanical models and predictive tools for understanding the spatial distribution of permeability in subsurface sandstone aquifers and reservoirs as determined by structural heterogeneities. In the subsurface, many faults, fractures, and deformation bands are below seismic resolution, and therefore are not detectable through conventional imaging techniques. These structural heterogeneities have a significant influence on fluid flow, acting either as conduits (open fractures) or barriers (low permeability fault rock and deformation bands) to fluid transport, and therefore are critical for many subsurface applications.

Project Description:
We conducted a broad-based research project to map and characterize structural heterogeneities (deformation bands, joints, sheared joints, and faults) in the Jurassic Aztec Sandstone exposed at the Valley of Fire State Park, Nevada, as an analog for active reservoirs and aquifers. Our efforts comprised complementary sub-projects: (1) orientation and distribution of compaction bands and the role of cross-bed orientation; (2) fluid flow through sandstones with intersection and overprinting structures such as compaction bands, joints, and faults; (3) modeling non-planar faults that can stick, slip, and open, and the associated damage; (4) modeling compaction bands and shear-enhanced deformation bands using Eshleby’s heterogeneity and discrete element methods. This integrated approach served to illuminate how a complex suite of brittle structures can evolve to affect fluid flow in a typical sandstone aquifer/reservoir at length scales from meters to kilometers.

Results:

The last leg of the project supervised by Aydin includes new research results as well as following up the publications of the earlier results as summarized below. Deng was Aydin's graduate student during the last four years.

(1) We have verified the hypothesis that cross beds their interplay with various boundary conditions control the occurrence, distribution and orientation of the compaction bands and joints in Aztec Sandstone in Valley of Fire State Park, Nevada. We have shown that the reason for this control is the anisotropy induced by the cross beds. These results were reported in journal articles by Deng and Aydin (2012), Deng and Aydin (2015), and Deng et al. (2015 (1)).

(2) We have determined permeability and porosity of compaction bands by Core Flooding laboratory experiments and Image Analysis and have suggested that compaction bands of various orientations have different porosity and permeability and that these differences also depend on the specific techniques employed. These results have been published in a journal article by Deng et al. (2015 (2)).

(3) We have followed up and have brought to a conclusion in a journal article modeling fluid flow through porous sandstone with overprinting and intersecting geological structures of various types (see Zhou et al., (2014).

(4) We have also resolved the relationship between the normal and strike-slip faults at the Valley of Fire State Park with implication to the mode of faulting in the entire Basin and Range (Aydin and de Joussineau, 2014).

(5) We have also characterized the texture and geostatistical properties of single compaction bands and zones of compaction bands (Torabi et al., 2015).

(6) We have documented various failure structures in shales and their impact on fluid flow (Aydin, 2014).

(7) In addition, an internet based book-encyclopedia entitle Rock Fracture Knowledgebase (Aydin and Zhong) which is large based on the Doe supported research is to be completed next year.

The last leg of the project supervised by Pollard produced new research results that are summarized here. Ritz was Pollard's graduate student and Meng and Liu were postdoctoral fellows supported by this DOE project.

(1) Meter-scale sub-vertical strike-slip fault traces exhibit geometric complexities that significantly contribute to their mechanical behavior (Ritz, E., Pollard, D. D., Ferris, M. 2015). Sections of faults that opened at depth channelized fluid flow, as evidenced by hydrothermal mineral infillings and alteration

haloes. Model results show that fault shape influences the distribution of opening, and consequently the spatial distribution of fluid conduits.

(2) Eshelby's solution for an ellipsoidal inhomogeneous inclusion in an infinite elastic body was applied to compaction and shear-enhanced compaction bands in the Aztec sandstone at Valley of Fire State Park, NV (Meng, C., Pollard, D. D., 2014). We generalized earlier results, limited to 2D and axisymmetric geometries, by considering ellipsoids with different intermediate and greatest axial lengths, consistent with field observations. Compaction strains of 1% to 10% produced significant triaxial compressive stress concentrations, which are responsible for band propagation.

(3) Analytical solutions for elastic properties and failure modes of a two-dimensional close-packed discrete element models were formulated, along with the conversion formulas between five inter-particle parameters of the lattice model and rock mechanical properties (Liu, C., Pollard, D. D., Shi, B., 2013). This model is applicable to the simulation of complicated structures that involve deformation and failure at different scales, but is particularly relevant to the formation of deformation bands in porous sandstone.

(4) Field observations were combined with microscopic analyses to investigate the mechanism of formation of wiggly compaction bands (CBs) in the porous Jurassic aeolian Aztec Sandstone exposed at Valley of Fire State Park, Nevada (Liu, C., D. D. Pollard, A. Aydin, and S. Deng, 2015). Band type varies continuously from chevron to wavy to straight where the porosity and grain sorting of the host rock increase systematically. We infer that the change from chevron to straight CBs is due to increasing failure angle of the sandstone and this may correlate with increasing grain sorting.

(5) To simulate the volumetric yielding failure of porous sandstone, a discrete element method was developed in which the element shrinks when the force state of one of its bonds reaches the yielding cap defined by the failure force and the aspect ratio (k) of the yielding ellipse (Liu, C., B. Shi, D. D. Pollard, and K. Gu, 2015). We conclude that the shape of wiggly CBs is controlled by the mechanical properties of sandstone, including the aspect ratio of the yielding ellipse, the critical yielding stress, and the cement strength, which are determined primarily by grain sorting, porosity, and cementation.

List of publications:

Aydin, A., 2014. Failure modes of shales and their implications for natural and man-made fracture assemblages. AAPG Bulletin, 98 (11), 2391-2409.

Aydin, A., de Joussineau, G., 2014. The relationship between normal and strike-slip faults in Valley of Fire State Park, Nevada, and its implications for stress rotation and partitioning of deformation in the east-central Basin and Range. Journal of Structural Geology, 63, 12-26.

Deng, S., Aydin, A., 2015. The strength anisotropy of localized compaction: A model for the role of the nature and orientation of cross-beds on the orientation and distribution of compaction bands in 3-D. Journal of Geophysical Research-Solid Earth, 120(3), 1523-1542.

Deng, S., Cilona, A., Morrow, C., Mapeli, C., Liu, C., Lockner, D., Prasad, M., Aydin, A., 2015 (1). Cross-bedding related anisotropy and its interplay with various boundary conditions in the formation and orientation of joints in an aeolian sandstone. Journal of Structural Geology, 77, 175-190.

Deng, S., Zuo, L., Aydin, A., Dvorkin, J., Mukerji, T., 2015 (2). Permeability characterization of natural compaction bands using core flooding experiments and 3D image-based analysis: Comparing and contrasting the results from two different methods. American Association of Petroleum Geologists Bulletin, 99(1), 27-49.

Liu, C., Pollard, D. D., Shi, B., 2013, Analytical solutions and numerical tests of elastic and failure behaviors of close-packed lattice for brittle rocks and crystals. Journal of Geophysical Research – Solid Earth, 118 (1): 71-82.

Liu, C., D. D. Pollard, A. Aydin, and S. Deng, 2015, Mechanism of formation of wiggly compaction bands in porous sandstone: 1. Observations and conceptual model, Journal of Geophysical Research - Solid Earth, 120, doi:10.1002/2015JB012372.

Liu, C., B. Shi, D. D. Pollard, and K. Gu, 2015, Mechanism of formation of wiggly compaction bands in porous sandstone: 2. Numerical simulation using discrete element method, J. Geophysical Research - Solid Earth, 120, doi:10.1002/2015JB012374.

Meng, C., Pollard, D. D., 2014, Eshelby's solution for ellipsoidal inhomogeneous inclusions with applications to compaction bands. Journal of Structural Geology, 67: 1-19.

Ritz, E., Pollard, D. D., Ferris, M. 2015, The influence of fault geometry on small strike-slip fault mechanics. Journal of Structural Geology, 73: 1-15.

Torabi, A., Aydin, A., Cilona, A., Jarsto, B. E., Deng, S., 2015. The dynamics and interaction of compaction bands in Valley of Fire State Park, Nevada (USA): Implications for their growth, evolution, and geostatistical property. Tectonophysics , 657, 113-128.

Zhou, X., Karimi-Fard, M., Durlofsky, L. J., Aydin, A., Spence, et al., G. H., 2014. Fluid flow through porous sandstone with overprinting and intersecting geological structures of various types: Advances in the Study of Fractured Reservoirs, The Geological Society, London, Special Publications, 374, doi 10.1144/SP374.11