GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 20, 2033, doi:10.1029/2003GL018449, 2003

Growth of deformation bands into echelon and ladder geometries

Richard A. Schultz and Clara M. Balasko[1]

Geomechanics–Rock Fracture Group, Department of Geological Sciences, Mackay School of Mines, University of Nevada, Reno, USA

Received 18 August 2003; accepted 29 August 2003; published 18 October 2003.

[1] We investigate the growth of cataclastic deformation bands in porous sandstone into Riedel, ladder, and "radiator rock" arrays. New field observations and mechanical modeling of DB growth using the distortional strain energy density criterion demonstrate that the physical control of these geometries is a contractional (mode-II) stepover between two echelon bands. Propagation of bands under pre-peak conditions, before Coulomb frictional sliding (faulting) begins, is not impeded by the echelon stepover geometry (as it is for brittle fractures under peak stress); continued in-plane growth of echelon bands creates ladders from stepovers. Successive addition of stepovers/ladders along their shearing direction produces Riedel geometries, whereas addition normal to strike produces radiator rock (the damage zone) as a consequence of strain hardening of bands and linked stepovers. The new framework has implications for fluid flow in groundwater aquifers, hydrothermal and precious metals systems, and petroleum fields. *INDEX TERMS:* 8010 Structural Geology: Fractures and faults; 8020 Structural Geology: Mechanics; 8025 Structural Geology: Mesoscopic fabrics; 8110 Tectonophysics: Continental tectonics—general (0905); 8159 Tectonophysics: Rheology—crust and lithosphere. **Citation:** Schultz, R. A., and C. M. Balasko, Growth of deformation bands into echelon and ladder geometries, *Geophys. Res. Lett.*, *30*(20), 2033, doi:10.1029/2003GL018449, 2003.

1. Introduction

[2] Porous rocks such as sandstones, limestones, pyroclastic tuffs, and some breccias form arrays of cataclastic deformation bands in response to shearing deformation, leading eventually to geometrically complex fault zones [*Aydin and Johnson*, 1978; *Shipton and Cowie*, 2001] that channel or impede (rather than facilitate) fluid flow. In the initial stages and when viewed parallel to the shearing direction, DBs form as single anastomosing or inosculating bands which strain-harden into stiff tabular inclusions [*Aydin and Johnson*, 1978, 1983]. Continued shearing localizes new bands in the adjacent, more deformable rock, leading to widening zones of cataclastic DBs that may have corrugated (but not faulted) contacts with host rock. Continued strain accumulation can lead to instability and nucleation of polished slip surfaces ("faulting" defined as Coulomb frictional sliding on discrete planes) either near the edge of the zone [*Aydin and Johnson*, 1978] or within it [*Shipton and Cowie*, 2001].

[3] Recently, *Davis* [1999] and *Davis et al.* [2000] documented echelon arrays of cataclastic deformation bands in southwestern Utah and interpreted them as conjugate Riedel sets of partially linked surfaces like those formed in soils and some rocks [*Tchalenko*, 1970]. These geometries become apparent when the arrays are viewed normal to the shearing direction [*Aydin and Johnson*, 1978; *Antonellini et al.*, 1994; *Antonellini and Aydin*, 1995; *Shipton and Cowie*, 2001], in contrast to the classic inosculating and parallel arrangements focused upon by Aydin and coworkers. A series of short parallel (linking) bands is observed to be bounded by longer zones of bands, forming open networks that *Davis* [1999] calls "ladder structures" or "radiator rock" (Figure 1a). These distinctive and fascinating patterns were observed previously [*Aydin*, 1978; *Aydin and Johnson*, 1978, 1983; *Antonellini et al.*, 1994] but were not emphasized in those studies. Similar geometries are observed in fault gouge [*Bartlett et al.*, 1981; *Gu and Wong*, 1994; *Marone*, 1998] and have been produced experimentally [*Mair et al.*, 2000]. Interestingly, the same geometry between echelon normal fault zones has also been reported from deep South African gold mines in Witwatersrand quartzite [*Gay and Ortlepp*, 1979; *Ortlepp*, 2000] (including the unusual "backward-breaking" linking band orientations, Figure 1b). Here in the quartzite, the linking structures within the stepover are also anticracks or compaction bands with shear [*Ortlepp*, 2000]. As a result, the genesis of ladder and Riedel-like arrays constitutes a general problem in strain localization and rock deformation.

[4] We examined DB arrays in several localities including Goblin Valley and Molley's Castle, Cottonwood Canyon, Sheets Gulch, Hillsdale Canyon (all in Utah), and Valley of Fire State Park, Nevada. At Goblin Valley/Molley's Castle, the arrays are pure dip-slip (normal) and the excellent exposures reveal characteristic and diagnostic geometries along both the mode-III [e.g., *Aydin and Johnson*, 1978] and mode-II [e.g., *Davis et al.*, 2000] directions. Oblique sections like that shown in Figure 1a and as typically found in Cottonwood and Hillsdale Canyons do not reveal the distinctions in band array geometry as clearly or definitively as the orthogonal sections found more commonly at Goblin Valley/Molley's Castle (e.g., Figure 1d). While the strike-slip arrays at Sheets Gulch are generally well exposed, our examinations suggest to us that incomplete exposures may have influenced *Ahlgren*'s [2001] interpretation of DB kinematics and timing. Our examination of more complete exposures at Sheets Gulch and as listed above reveals instead that linking bands (Figure 1) rarely extend into the surrounding host rock from an array without a corresponding bounding band being present at some greater distance.

---

[1] Now at SRK Consulting, Reno, Nevada, USA.

0094-8276/03/2003GL018449$05.00

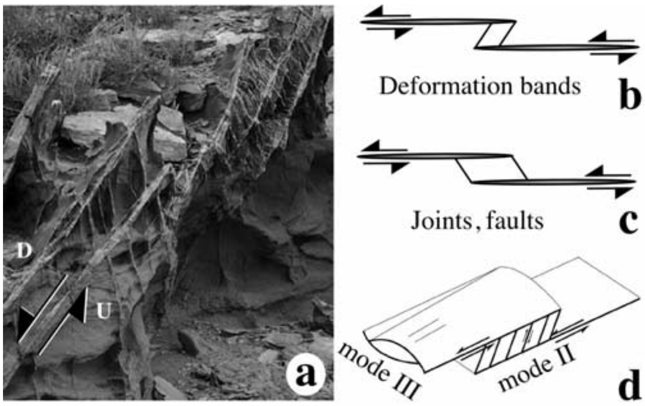

Figure 1. Geometry of deformation bands viewed normal to shearing direction. (a). Outcrop near Goblin Valley, Utah [*Fossen and Hesthammer*, 1997] showing bounding bands connected by regularly spaced linking bands. U, up; D, down. Total width of zone ~1m. (b). Geometry of echelon deformation bands. (c). Geometry of echelon cracks (mode-I) and faults (mode-II). (d). 3-D geometry of the interacting DB pair.

[5] Our field observations of these DB arrays (in sandstone) confirm that the linking bands form preferentially within overlapping deformation bands [*Davis et al.*, 2000; *Ahlgren*, 2001], suggesting that increased stress magnitudes between overlapping bands [*McGarr et al.*, 1979] facilitated localization of the linking bands. Bands having the same orientation as the linking bands occur in isolation and far from stepovers, however ("conjugate" bands [*Davis*, 1999; *Ahlgren*, 2001]), suggesting that the orientations of both linking and conjugate bands (as opposed to their particular location [*Davis*, 1999]) are closely related to the far-field stress state [*Balasko*, 2003]. This potentially confusing relationship can be easily resolved by ascertaining the presence of bounding bands. The linking bands form only between overlapping or parallel ("bounding") DBs as long as the spacing between the bounding bands is sufficiently small (e.g., *Ahlgren*'s [2001] Figure 4a); overlapping bands having wide spacings are not associated with linking bands. Conjugate bands may crosscut a bounding band (to which they are not related) whereas linking bands are contained within a pair of bounding bands.

[6] The DB arrays studied (Figure 1) have been described as Riedel shear zones by *Davis* [1999], *Davis et al.* [2000], and *Ahlgren* [2001], with the bounding bands corresponding to R-shears [e.g., *Tchalenko*, 1970; *Bartlett et al.*, 1981] and the linking bands to (conjugate) R′-shears. This interpretation is somewhat different than classic Riedel shearing in rocks, in which R-shears are connected by P-shears [e.g., *Tchalenko*, 1970; *Bartlett et al.*, 1981]. The growth of particular types of Riedel shears (e.g., R′- or T-shears) depends on the physical properties of the deforming material [e.g., *Bartlett et al.*, 1981]. These observations suggest a response of the host sandstone (and Witwatersrand quartzite) to shearing that favors growth of DBs in conjugate R′-shear orientations, most likely as a result of particular (pre-peak) localization mechanisms of bounding and linking bands (see section 3).

[7] Our work motivates an alternative physical explanation for the growth of Riedel geometries described by Davis and colleagues. We interpret the fundamental unit of all three geometries (Riedel, ladder, and radiator) as a contractional echelon stepover between two closely spaced deformation bands (Figure 1b) that function as fractures (i.e., stress concentrators and redistributors). Although this geometry was noted previously [e.g., *Davis et al.*, 2000], the mechanical basis and consequences were not. The linking bands of ladder and Riedel structures nucleate preferentially between the echelon stepovers, but with an orientation opposite to that characteristic of linking brittle fractures (cracks, faults) formed in either mode-I or mode-II echelon fracture sets (Figure 1c) and opposite to classic Riedel geometry (R′-shears instead of P-shears). The 3-D geometry of the simplest DB array is best described as a pair of DB surfaces that interact differently depending on the viewing direction (Figure 1d) but which share the same kinematics (e.g., overall shearing sense).

2. Methods

[8] We investigate the growth of DB arrays by modeling the growth of an echelon pair of (bounding) bands for a variety of bounding-band spacings and configurations. DB interaction and growth are modelled by using a numerical boundary element [*Crouch and Starfield*, 1983] computer program (FAULT [*Schultz*, 1992]) that solves for the displacement distribution on discretized bands due to the remote stress state and constitutive relations. Far-field stresses and constitutive relations along the bands are prescribed along with the band geometry. Solution of the resulting matrix of equations provides the predicted displacement distribution along the echelon bands, which then can be used to calculate the inhomogeneous stresses and local stress trajectories within the stepover that permit predictions of band growth locations and directions.

[9] Far-field compressive stresses are taken to be σ_{max} = 50 MPa and σ_{min} = 37.5 MPa, with σ_{max} oriented at 25° to the plane of the band (Figure 2). These values are less then the compressive strength of porous Entrada Sandstone (~48 MPa for the ~19% porosity host rock [*Lama and Vutukuri*, 1978]). The imposed stress ratio of $\sigma_{max}/\sigma_{min}$ = 1.3 is less than that required for frictional sliding along the bands ($\geq$ 3.1, assuming typical friction coefficients of ~0.6 or greater), as indicated by the field observations of non-slipped (non-faulted) bands, but sufficient to give the displacement-length relation δ/L = 0.005 measured across natural bands [*Fossen and Hesthammer*, 1997] (for map lengths $L \sim 1-10$ m), with δ being the mode-II maximum shearing displacement between passive markers on either side of the band. The 25° angle is obtained from the average dip of conjugate normal-offset deformation bands in the Goblin Valley/Molley's Castle area (60–70°; R. A. Schultz and H. Fossen, unpublished data). Host rock is taken to have Young's modulus E = 18.2 GPa, shear modulus G = 7.9 GPa, and Poisson's ratio 0.15 [*Lama and Vutukuri*, 1978]. Our results are insensitive to modest variations in these parameters.

[10] Bands are modeled as "seam" elements [*Crouch and Starfield*, 1983, pp. 208–210] with maximum continuous shearing displacements δ across their $T \sim 1$ mm thickness. A reduced ("equivalent") shear modulus G_{eq} is calculated from measured shear strain across the bands of $\delta/T \sim 0.1$ (R. A. Schultz and H. Fossen, unpublished data) and the remote shear stress resolved onto the band using [*Crouch*

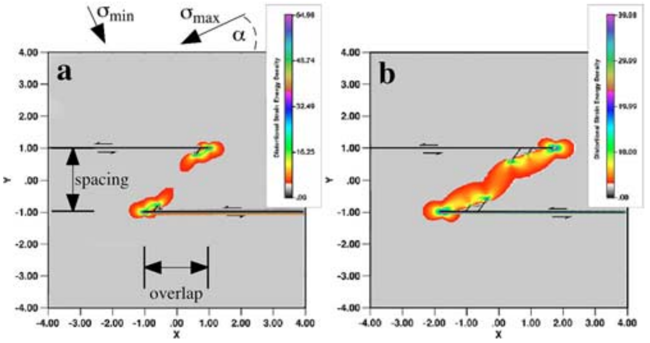

Figure 2. Representative results of boundary element simulation of DB growth at spacings s normalized by DB half-length k of $s/k = 0.18$. Color bar and contours show values of distortional strain energy density near the bands normalized by that calculated for host rock far from the bands. Earlier (underlapped) stages calculated but not shown (for $-0.3 \leq o/k \leq 0.0$); only overlapped configurations (a and b; $o/k > 0$) produce linking bands (small ticks extending into the stepover). Note regular spacing of new linking bands produced in the wake of the propagating bounding band's tip. Results shown are comparable to those computed (but not shown) for smaller and larger band spacings ($s/k = 0.09$, 0.55) and for larger band overlaps ($o/k < 1.1$); all of these produce ladders with linking bands.

and Starfield, 1983] $|\tau_{xy}| = |2G\varepsilon_{xy}| = |G(\delta/T)|$, giving $G_{eq} = 0.31$ GPa. A larger value of Young's modulus E_b was used for the bands (relative to host rock) to simulate their compaction, although specific values are unconstrained from field or laboratory measurements. We find after exploring a range of E_b for the bands that band-normal stiffness exerts only a small influence on the distortional strain energy density, implying that a band's normal displacement component is relatively unimportant in predictions of shear band linkage and propagation.

[11] The locations and orientations of new DB segments, either as propagating bounding bands or newly forming linking bands, are predicted by using distortional strain energy density [*Du and Aydin*, 1993] calculated around the band array. This criterion relates the band's shear offset δ to distortions of host rock adjacent to it under pre-peak (pre-faulting) conditions, consistent with the lack of frictional sliding along bands or in the adjacent deforming host rock. Building on previously published numerical simulations of the incremental growth of echelon crack [e.g., *Olson*, 1993] and fault [*Du and Aydin*, 1993] sets, we use distortional strain energy density to identify the locations and orientations of new band segments for small increments of deformation and then continue and rerun the simulation with the addition of these new DB segments. As a result, we can simulate the progressive development of geometrically complex DB arrays, and our numerical experiments compare quite favorably with the exposures mapped in the field.

3. Results

[12] Our numerical boundary element models that assume pre-peak conditions successfully predict the geometries and sequence observed in the field (Figure 2), in contrast to previous work [*McGarr et al.*, 1979; *Leem*, 1995] that related DB growth to frictional sliding and fault development under peak stress levels. Indeed, use of a peak-strength criterion (i.e., faulting), such as Coulomb, Modified Griffith, or Hoek-Brown, in our models instead of pre-peak distortional strain energy density fails to predict either the in-plane propagation of bounding bands or the formation or orientations of linking bands, in conflict with the field observations.

[13] Interestingly, our calculations reveal that overlapping geometries of echelon DBs do not "freeze" with overlap/spacing ratios of $\sim 1-3$, as is common for brittle echelon joint and fault systems [e.g., *Aydin and Nur*, 1982]. Instead, the echelon (bounding) DBs continue to propagate in-plane, at a given value of spacing, to indefinitely large values of overlap, leading to parallel bounding bands with "ladder" geometries (Figures 2 and 3a). Such in-plane growth of mode-II fractures has been observed in experiments [e.g., *Lockner et al.*, 1991; *Fossen and Gabrielsen*, 1996] and is related to the particular mode of fracture propagation (i.e., pre-peak shearing). Linking bands at the correct ("z"-shaped) orientation (Figure 1b) are predicted from our simulations to form in alternation with successive increments of bounding-band growth, producing linking bands having a regular spacing that scales with the spacing between the bounding bands (calculated but not shown). This systematic relationship between the spacings of linking and bounding bands, known from the field [*Antonellini and Aydin*, 1995], can be related to the progressive development of contractional stepovers into ladders.

4. Discussion and Conclusions

[14] As the echelon DBs grow into an overlapped configuration (with a contractional stepover), the mechanical

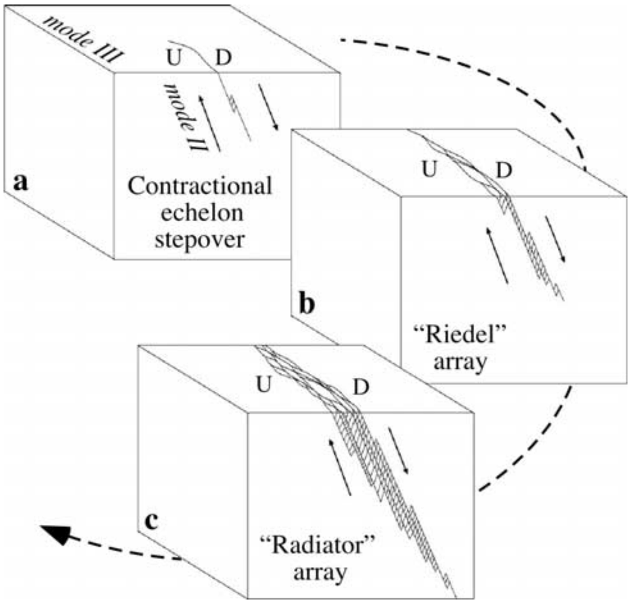

Figure 3. Sequential growth of DB arrays by addition of contractional echelon stepovers. (a). Ladders form as stepovers having given spacing but indefinitely large overlaps. (b). Geometries interpreted as Riedel shear zones form by in-plane addition of stepovers in the downdip direction. (c). Radiator rock geometries form by addition of stepovers in the cross-strike direction.

interaction between them is sufficient to promote the growth of linking bands into the stepover but insufficient to shut down propagation of the bounding bands. As a result, echelon DBs grow into ladders. Once a contractional stepover between echelon DBs is formed (Figure 1b; initially in an underlapping configuration), it can continue to grow parallel to its overall strike with the same sense of step [*Du and Aydin*, 1991]; this underlying mechanism of near-field mechanical interaction is how a Riedel fracture geometry is formed (Figure 3b). Our observations and calculations suggest a natural progression from contractional echelon stepovers (Figures 1b and 3a) to ladders and Riedel arrays by successive in-plane addition of DB sets (Figure 1d) in the downdip (shearing) direction (Figure 3b).

[15] Strain hardening of individual bands leads to nucleation of new bands adjacent to previous ones and consequent widening of the resulting zone [e.g., *Aydin and Johnson*, 1978; *Antonellini and Aydin*, 1995]. This scenario was originally identified for a DB array when viewed parallel to shearing (the mode-III sense; Figure 1d). We infer that widening of the DB zone in mode III also requires the addition of new contractional echelon stepovers in mode II (i.e., ladders). Because the "backward-breaking" stepover geometry of DBs (Figure 1b) is geometrically less efficient in accommodating large shearing displacements than the "forward-breaking" geometry (Figure 1c), the mode-II arrays may themselves lock up and, in conjunction with strain hardening of the bands, further promote widening of the DB zone. We infer that cross-strike widening of the array as strain hardening and kinematic lock-up proceed likely leads eventually to the spatially distributed "radiator rock" geometry noted by *Davis* [1999] and identified as the pre-fault "damage zone" [e.g., *Shipton and Cowie*, 2003] (Figure 3c). As a result, formation of fluid compartments and flow barriers, along with the damage zone and overall fault-zone architecture, follows a systematic and progressive sequence (Figure 3) that hinges on the mechanism of fracture localization.

[16] **Acknowledgments.** This work was supported by the donors of the Petroleum Research Fund of the American Chemical Society, and by NASA's Planetary Geology and Geophysics Program. Thanks to Raj Siddharthan (UNR) for suggesting equivalent shear modulus. Detailed and thoughtful reviews by George Davis and Karen Mair helped sharpen the final paper.

References

Ahlgren, S. G., The nucleation and evolution of Riedel shear zones as deformation bands in porous sandstone, *J. Struct. Geol.*, *23*, 1203–1214, 2001.

Antonellini, M., and A. Aydin, Effect of faulting on fluid flow in porous sandstones: Geometry and spatial distribution, *Am. Assoc. Petrol. Geol. Bull.*, *79*, 642–671, 1995.

Antonellini, M., A. Aydin, and D. D. Pollard, Microstructure of deformation bands in porous sandstones at Arches National Park, Utah, *J. Struct. Geol.*, *16*, 941–959, 1994.

Aydin, A., Small faults formed as deformation bands in sandstone, *Pure Appl. Geophys.*, *116*, 913–930, 1978.

Aydin, A., and A. Johnson, Development of faults as zones of deformation bands and as slip surfaces in sandstone, *Pure Appl. Geophys.*, *116*, 931–942, 1978.

Aydin, A., and A. Johnson, Analysis of faulting in porous sandstones, *J. Struct. Geol.*, *5*, 19–31, 1983.

Aydin, A., and A. Nur, Evolution of pull-apart basins and their scale independence, *Tectonics*, *1*, 11–21, 1982.

Balasko, C. M., Mechanism and Sequence of Formation of Deformation Bands into Spatially Localized or Distributed Sets: Ladders, Riedels, and Echelon Arrays of Utah, M.S. thesis, University of Nevada, Reno, 2003.

Bartlett, W. L., M. Friedman, and J. M. Logan, Experimental folding and faulting of rocks under confining pressure, Part IX., Wrench faults in limestone layers, *Tectonophysics*, *79*, 255–277, 1981.

Crouch, S. L., and A. M. Starfield, *Boundary Element Methods in Solid Mechanics*, George Allen & Unwin, 1983.

Davis, G. H., Structural geology of the Colorado Plateau region of southern Utah, with special emphasis on deformation bands, *Geol. Soc. Am. Spec. Pap.*, *342*, 157 pp, 1999.

Davis, G. H., A. P. Bump, P. E. García, and S. G. Ahlgren, Conjugate Riedel deformation band shear zones, *J. Struct. Geol.*, *22*, 169–190, 2000.

Du, Y., and A. Aydin, Interaction of multiple cracks and formation of echelon crack arrays, *Int. J. Num. Anal. Meth. Geomech.*, *15*, 205–218, 1991.

Du, Y., and A. Aydin, The maximum distortional strain energy density criterion for shear fracture propagation with applications to the growth paths of *en échelon* faults, *Geophys. Res. Lett.*, *20*, 1091–1094, 1993.

Fossen, H., and R. H. Gabrielsen, Experimental modelling of extensional fault systems by use of plaster, *J. Struct. Geol.*, *18*, 673–689, 1996.

Fossen, H., and J. Hesthammer, Geometric analysis and scaling relations of deformation bands in porous sandstone, *J. Struct. Geol.*, *18*, 1–16, 1997.

Gay, N. C., and W. D. Ortlepp, Anatomy of a mining-induced fault zone, *Geol. Soc. Am. Bull.*, *90*, 47–58, 1979.

Gu, Y., and T.-f. Wong, Development of shear localization in simulated quartz gouge: Effects of cumulative slip and gouge particle size, *Pure Appl. Geophys.*, *143*, 387–423, 1994.

Lama, R. D., and V. S. Vutukuri, *Handbook on Mechanical Properties of Rocks*. Vol. II: *Testing Techniques and Results*, Trans Tech Publications, Switzerland, 1978.

Leem, J., Finite Element Analysis of Elastic Interaction of Two En Echelon Overlapping Faults, MS thesis, Texas A&M University, 1995.

Lockner, D. A., J. D. Byerlee, V. Kuksenko, A. Ponomarev, and A. Sidorin, Quasi-static fault growth and shear fracture energy in granite, *Nature*, *350*, 39–42, 1991.

Mair, K., I. Main, and S. Elphick, Sequential growth of deformation bands in the laboratory, *J. Struct. Geol.*, *22*, 25–42, 2000.

Marone, C., Laboratory-derived friction laws and their application to seismic faulting, *Ann. Rev. Earth Planet. Sci.*, *26*, 643–696, 1998.

McGarr, A., D. D. Pollard, N. C. Gay, and W. D. Ortlepp, Observations and analysis of structures in exhumed mine-induced faults, in *Proceedings of Conference VIII: Analysis of Actual Fault Zones in Bedrock*, *U.S. Geological Survey Open-File Report 79-1239*, 101–120, 1979.

Olson, J. E., Joint pattern development: Effects of subcritical crack growth and mechanical crack interaction, *J. Geophys. Res.*, *98*, 12,251–12,265, 1993.

Ortlepp, W. D., Observation of mining-induced faults in an intact rock mass at depth, *Int. J. Rock Mech. Min. Sci.*, *37*, 423–436, 2000.

Schultz, R. A., Mechanics of curved slip surfaces in rock, *Eng. Anal. Bound. Elements*, *10*, 147–154, 1992.

Shipton, Z. K., and P. A. Cowie, Damage zone and slip-surface evolution over μm to km scales in high-porosity Navajo sandstone, Utah, *J. Struct. Geol.*, *23*, 1825–1844, 2001.

Shipton, Z. K., and P. A. Cowie, A conceptual model for the origin of fault damage zone structures in high-porosity sandstone, *J. Struct. Geol.*, *25*, 333–344, 2003.

Tchalenko, J. S., Similarities between shear zones of different magnitudes, *Geol. Soc. Am. Bull.*, *81*, 1625–1640, 1970.

C. M. Balasko, SRK Consulting, 5250 Neil Rd. Suite 300, Reno, NV 89502, USA. (cbalasko@srk.com)

R. A. Schultz, Geomechanics–Rock Fracture Group, Department of Geological Sciences/172, Mackay School of Mines, University of Nevada, Reno, NV 89557-0138, USA. (schultz@mines.unr.edu)