Research Focus: Significance of large-displacement, low-angle normal faults

Gary J. Axen*
Department of Earth & Environmental Science, New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801, USA

Low-angle normal faults (LANFs or detachment faults; dip <30°) are a major class of faults that became widely accepted by earth scientists only in the late twentieth century. Continental LANFs were mapped for nearly 100 yr (e.g., Ransome et al., 1910) but typically were interpreted as odd thrust faults, mega-landslide faults, or nonconformities. This changed with the recognition of LANFs in widespread association with Tertiary metamorphic tectonites (e.g., Davis and Coney, 1979; Crittenden et al., 1980), and we now know that individual LANFs in the Basin and Range province slipped 5–50 km, and several LANFs exhumed mid-crustal rocks (Anderson, 1971; Armstrong, 1972; Wright and Troxel, 1973; Wernicke, 1981; Wernicke et al., 1988). LANFs are globally significant; they occur in much of the geologic record (e.g., Holm, 1996; Axen et al., 1999), on most continents, in both extensional and contractional settings (e.g., Selverstone, 1988; Burchfiel et al., 1992), and at slow-spreading mid-ocean ridges (e.g., Tucholke and Lin, 1998). LANFs continue to be central topics at the Geological Society of America Penrose Conferences (Cordilleran metamorphic core complexes, 1977; Exhumation processes, 1996; Extending a continent, 2007) and were prominent in the U.S. National Science Foundation (NSF) MARGINS Rupturing Continental Lithosphere Science Plan (National Science Foundation, 2003).

Here, I review the significance of, and debates about, continental LANFs, which remain controversial because (1) they do not conform to current fault-mechanical theory, and (2) there is little strong evidence for major (M > 6) LANF earthquakes (Jackson and White, 1989; Collettini and Sibson, 2001). Nevertheless, several LANFs originated and slipped in the brittle crust as primary, gently dipping normal faults (Wernicke et al., 1985; Wernicke, 1995; Axen, 2004). This requires reevaluation of current fault mechanical theory that predicts only steep (~60°) normal faults in the brittle crust (Anderson, 1942) and frictional lock up of existing normal faults at ~30° dip (Collettini and Sibson, 2001), at which point new steep faults "should" form.

Some LANFs clearly were rotated from steep to gentle dips. Some rotated while slipping, with intervening blocks, like books falling over on a shelf (Morton and Black, 1975; Proffett, 1977; Chamberlin, 1983), and others rotated passively to low dips. Spencer (1984) recognized an isostatic mechanism that tilts LANFs: as the upper-plate load is withdrawn laterally, the footwall progressively rebounds and arches into a dome, rotating the LANF to gentler, even opposite, dips. This "rolling hinge" mechanism was later invoked to rotate steep normal faults to gentle dips (Wernicke and Axen, 1988; Buck, 1988), but compelling continental examples are unknown (Axen and Bartley, 1997).

Garcés and Gee (2007; this issue of *Geology*) argue, using paleomagnetic inclination data, for 50°–80° of dip decrease of oceanic detachment faults along the slow-spreading Mid-Atlantic Ridge, the first LANFs likely to have been rotated significantly by the rolling hinge mechanism (lack of declination data leaves some ambiguity). This implies fundamental differences between oceanic and continental LANFs, emphasizing the need for more study and comparison of both.

Normal faults that slip at low dips inform the heated debate about the strength of natural faults (e.g., Rice, 1992). LANF slip requires either low apparent fault friction relative to laboratory values (Byerlee, 1978) or rotation of the stress field around the faults. Sparse observations do not support the latter hypothesis (Reynolds and Lister, 1987; Axen and Selverstone, 1994), suggesting that LANFs are frictionally weak due to high fluid pressure or weak fault-zone materials. Like LANFs, the San Andreas fault appears weaker than laboratory measurements imply (Lachenbruch and Sass, 1980; Zoback et al., 1987), which motivates the SAFOD (San Andreas Fault Observatory at Depth) component of the NSF EarthScope Program.

Formation of brittle normal faults with low initial dips is an unsolved mechanical problem. It requires (1) rotation of the stress field as the LANF is approached (Yin, 1989, Spencer and Chase 1989; but compare Buck, 1990), and/or (2) other special and unusual(?) mechanical, boundary, and initial conditions (e.g., Westaway, 1999), or suggests that we do not understand how to apply laboratory results on the fracture of intact rocks to natural time and space scales (e.g., Anderson, 1942).

LANFs also are significant for understanding seismicity. Although controversial, some historical earthquakes probably did involve LANF slip (Axen, 1999; Abers, 2001), and strong evidence exists for LANF paleoseismicity (e.g., John, 1987; Axen et al., 1999). If such events do occur, then their low historical frequency suggests that LANF earthquakes may be rare but large (Wernicke, 1995). Alternatively, a trigger may be needed to overcome static frictional resistance to seismogenic slip (Axen, 1999). Either way, some major cities (e.g., Salt Lake City, Utah) may be at risk from LANF earthquakes. Also, it appears that special attention to seismic records is required to identify LANF earthquakes (see Axen, 1999). Of course, the instrumental seismic record simply may be too short to have captured an unambiguous LANF event. If LANFs are not seimogenic, then they are the first known class of faults to slip only by creep, and they may hold the key to frictional stability versus instability on natural faults.

The footwalls of large-slip LANFs record the history of the midcrust, both during and before extension. For example, isostatic LANF footwall rebound requires compensation by a medium of crustal, not mantle, density (Block and Royden, 1990; Wernicke, 1990). This confirmed the concept that crustal asthenospheric layers exist, and allowed characterization of their viscosity (Kruse et al., 1991, Wdowinski and Axen, 1992) and of the local flexural rigidity of the upper crust (Spencer, 1984; Buck, 1988). LANFs also hold important clues to the evolution and dynamics of the strongest part of the continental crust, the brittle-ductile transition (Brace and Kohlstedt, 1980), which is less well understood than the weaker over- and underlying brittle or ductile parts. Many LANFs evolved from ductile shear zones into brittle faults as removal of the insulating hanging walls cooled the footwall shear zones (Davis and Coney, 1979). These record shear-zone evolution in the brittle-ductile transition (Axen et al., 2001).

To date, most major scientific results from LANFs come from exposed continental examples, due to their easy access, but breakthroughs can be anticipated from the increasing study of LANFs at mid-ocean ridges (Garcés and Gee, 2007), where crustal structure and evolution are very different (and simpler) than in continental settings. The potential is great for data from oceanic LANFs to influence our understanding of mid-ocean ridge processes and dynamics, especially combined with knowledge of spreading rates and crustal structure, and with analogs from ancient ophiolites. Comparison of oceanic and continental LANF complexes should open new doorways to understanding the dynamics of crustal deformation and evolution.

ACKNOWLEDGMENTS

S. Bilek and J. Selverstone provided helpful reviews.

---

*Email: gaxen@ees.nmt.edu

Geology, March 2007; v. 35; no. 3; p. 287–288.

REFERENCES CITED

Abers, G.A., 2001, Evidence for seismogenic normal faults at shallow dips in continental rifts, *in* Wilson, R.C.L., Taylor, B., and Froitzheim, N., eds., Nonvolcanic rifted margins: Geological Society Special Publication 187, p. 305–318.

Anderson, E.M., 1942, The dynamics of faulting and dyke formation with application to Britain: Edinburgh, Oliver and Boyd, 191 p.

Anderson, R.E., 1971, Thin-skin distension in Tertiary rocks of southwestern Nevada: Geological Society of America Bulletin, v. 82, p. 43–58, doi: 10.1130/0016-7606(1971)82[43:TSDITR]2.0.CO;2.

Armstrong, R.L., 1972, Low-angle (denudation faults), hinterland of the Sevier orogenic belt, eastern Nevada and western Utah: Geological Society of America Bulletin, v. 83, p. 1729–1754, doi: 10.1130/0016-7606(1972)83[1729:LDFHOT]2.0.CO;2.

Axen, G.J., 1999, Low-angle normal fault earthquakes and triggering: Geophysical Research Letters, v. 26, p. 3693–3696, doi: 10.1029/1999GL005405.

Axen, G.J., 2004, Mechanics of low-angle normal faults, *in* Karner, G., Taylor, B., Driscoll, N., and Kohlstedt, D.L., eds., Rheology and deformation in the lithosphere at continental margins: New York, Columbia University Press, p. 46–91.

Axen, G.J., and Bartley, J.M., 1997, Field test of rolling hinges: Existence, mechanical types, and implications for extensional tectonics: Journal of Geophysical Research, v. 102, p. 20,515–20,537, doi: 10.1029/97JB01355.

Axen, G.J., and Selverstone, J., 1994, Stress-state and fluid-pressure level along the Whipple detachment fault, California: Geology, v. 22, p. 835–838, doi: 10.1130/0091-7613(1994)022<0835:SSAFPL>2.3.CO;2.

Axen, G.J., Fletcher, J.M., Cowgill, E., Murphy, M., Kapp, P., MacMillan, I., Ramos-Velázquez, E., and Aranda-Gómez, J., 1999, Range-front fault scarps of the Sierra El Mayor, Baja California: Formed above an active low-angle normal fault?: Geology, v. 27, p. 247–250, doi: 10.1130/0091-7613(1999)027<0247:RFFSOT>2.3.CO;2.

Axen, G.J., Selverstone, J., and Wawrzyniec, T., 2001, High-temperature embrittlement of extensional Alpine mylonite zones in the midcrustal ductile-brittle transition: Journal of Geophysical Research, v. 106, p. 4337–4348, doi: 10.1029/2000JB900372.

Block, L., and Royden, L.H., 1990, Core complex geometries and regional scale flow in the lower crust: Tectonics, v. 9, p. 557–567.

Brace, W.F., and Kohlstedt, D.L., 1980, Limits on lithospheric stress imposed by laboratory experiments: Journal of Geophysical Research, v. 85, p. 6248–6252.

Buck, W.R., 1988, Flexural rotation of normal faults: Tectonics, v. 7, p. 959–973.

Buck, W.R., 1990, Comment on “Origin of regional rooted low-angle normal faults: A mechanical model and it implications” by An Yin: Tectonics, v. 9, no. 3, p. 545–546.

Burchfiel, B.C., Zhiliang, C., Hodges, K.V., Yuping, L., Royden, L.H., Changrong, D., and Jiene, X., 1992, The south Tibetan detachment system, Himalayan orogen: Extension contemporaneous with and parallel to shortening in a collisional mountain belt: Geological Society of America Special Paper 269, 41 p.

Byerlee, J., 1978, Friction of rocks: Pure and Applied Geophysics, v. 116, p. 615–626, doi: 10.1007/BF00876528.

Chamberlin, R.M., 1983, Cenozoic domino-style crustal extension in the Lemitar Mountains, New Mexico: A summary, *in* Chapin, C.E., and Callender, J.F., eds., Guidebook, 34th Field Conference, Socorro Region II, Volume 34: Socorro, New Mexico, New Mexico Geological Society, p. 111–118.

Collettini, C., and Sibson, R.H., 2001, Normal faults, normal friction?: Geology, v. 29, p. 927–930, doi: 10.1130/0091-7613(2001)029<0927:NFNF>2.0.CO;2.

Crittenden, M.D., Coney, P.J., and Davis, G.H., 1980, Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 490.

Davis, G.H., and Coney, P.J., 1979, Geologic development of Cordilleran metamorphic core complexes: Geology, v. 7, p. 120–124, doi: 10.1130/0091-7613(1979)7<120:GDOTCM>2.0.CO;2.

Garcés, M., and Gee, J.S., 2007, Paleomagnetic evidence of large footwall rotations associated with low-angle normal faults at the Mid-Atlantic Ridge: Geology, v. 35, p. 279–282.

Holm, D.K., 1996, Core complex model proposed for gneiss dome development during collapse of the Paleoproterozoic Penokean Orogen, Minnesota: Geology, v. 24, p. 343–346, doi: 10.1130/0091-7613(1996)024<0343:CCMPFG>2.3.CO;2.

Jackson, J.A., and White, N.J., 1989, Normal faulting in the upper continental crust: Observations from regions of active extension: Journal of Structural Geology, v. 11, p. 15–36, doi: 10.1016/0191-8141(89)90033-3.

John, B.E., 1987, Geometry and evolution of a mid-crustal extensional fault system: Chemehuevi Mountains, southeastern California, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental extensional tectonics: Geological Society Special Publication 28, p. 313–336.

Kruse, S., McNutt, M., Phippes-Morgan, J., Royden, L., and Wernicke, B., 1991, Lithospheric extension near Lake Mead, Nevada: A model for ductile flow in the lower crust: Journal of Geophysical Research, v. 96, p. 4435–4456.

Lachenbruch, A.H., and Sass, J., 1980, Heat flow and energetics of the San Andreas fault zone: Journal of Geophysical Research, v. 85, p. 6185–6222.

Morton, W.H., and Black, R., 1975, Crustal attenuation in Afar, *in* Pilgar, A., and Rosler, A., eds., Proceedings of the International symposium on the Afar region and related rift problems, Volume Report 14: Stuttgart, Germany, E. Schweitzerbart’sche verlagbuchhandlung, p. 55–65.

National Science Foundation, 2003, NSF MARGINS Science Plans 2004: New York, Lamont-Doherty Earth Observatory of Columbia University, 170 p.

Proffett, J.M., Jr., 1977, Cenozoic geology of the Yerington District, Nevada, and implications for nature and origin of Basin and Range faulting: Geological Society of America Bulletin, v. 88, p. 247–266, doi: 10.1130/0016-7606(1977)88<247:CGOTYD>2.0.CO;2.

Ransome, F.L., Emmons, W.H., and Garrey, G.H., 1910, Geology and ore deposits of the Bullfrog district, Nevada: U.S. Geological Survey Bulletin, v. 407, p. 1–130.

Reynolds, S.J., and Lister, G.S., 1987, Structural aspects of fluid-rock interaction in detachment zones: Geology, v. 15, p. 362–366, doi: 10.1130/0091-7613(1987)15<362:SAOFII>2.0.CO;2.

Rice, J.R., 1992, Fault stress states, pore pressure distributions, and the weakness of the San Andreas fault, *in* Evans, B., and Wong, T.-F., eds., Fault mechanics and transport properties of rocks: A festschrift in honor of W.F. Brace: New York, Academic Press, p. 475–504.

Selverstone, J., 1988, Evidence for east-west crustal extension in the eastern Alps: Implications for the unroofing history of the Tauern window: Tectonics, v. 7, p. 87–105.

Spencer, J.E., 1984, The role of tectonic denudation in the warping and uplift of low-angle normal faults: Geology, v. 12, p. 95–98, doi: 10.1130/0091-7613(1984)12<95:ROTDIW>2.0.CO;2.

Spencer, J.E., and Chase, C.G., 1989, Role of crustal flexure in initiation of low-angle normal faults and implications for structural evolution of the Basin and Range province: Journal of Geophysical Research, v. 94, p. 1765–1775.

Tucholke, B.E., and Lin, J., 1998, Megamullions and mullion structures defining oceanic metamorphic core complexes on the Mid-Atlantic Ridge: Journal of Geophysical Research, v. 103, p. 9857–9866, doi: 10.1029/98JB00167, doi: 10.1029/98JB00167.

Wdowinski, S., and Axen, G.J., 1992, Isostatic rebound due to tectonic denudation: A viscous flow model of a layered lithosphere: Tectonics, v. 11, p. 303–315.

Wernicke, B., 1981, Low-angle normal faults in the Basin and Range Province: Nappe tectonics in an extending orogen: Nature, v. 291, p. 645–648, doi: 10.1038/291645a0.

Wernicke, B., 1990, The fluid crustal layer and its implications for continental dynamics, *in* Salisbury, M.H., and Fountain, D.M., eds., Exposed cross sections of the continental crust: Netherlands, Kluwer Academic Publishers, p. 509–544.

Wernicke, B., 1995, Low-angle normal faults and seismicity: A review: Journal of Geophysical Research, v. 100, p. 20,159–20,174, doi: 10.1029/95JB01911.

Wernicke, B., and Axen, G.J., 1988, On the role of isostasy in the evolution of normal fault systems: Geology, v. 16, p. 848–851, doi: 10.1130/0091-7613(1988)016<0848:OTROII>2.3.CO;2.

Wernicke, B., Walker, J.D., and Beaufait, M.S., 1985, Structural discordance between Neogene detachments and frontal Sevier thrusts, central Mormon Mountains, southern Nevada: Tectonics, v. 4, p. 213–246.

Wernicke, B., Axen, G.J., and Snow, J.K., 1988, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada: Geological Society of America Bulletin, v. 100, p. 1738–1757, doi: 10.1130/0016-7606(1988)100<1738:BARETA>2.3.CO;2.

Westaway, R., 1999, The mechanical feasibility of low-angle normal faulting: Tectonophysics, v. 308, p. 407–443, doi: 10.1016/S0040-1951(99)00148-1.

Wright, L.A., and Troxel, B.W., 1973, Shallow-fault interpretation of Basin and Range structure, southwestern Great Basin, *in* de Jong, K.A., and Scholten, R., eds., Gravity and tectonics: New York, John Wiley and Sons, p. 397–407.

Yin, A., 1989, Origin of regional rooted low-angle normal faults: A mechanical model and its implications: Tectonics, v. 8, p. 469–482.

Zoback, M.D., Zoback, M.L., Mount, V.S., Suppe, J., Eaton, J.P., Healy, J.H., Oppenheimer, D., Reasenberg, P., Jones, L., Raleigh, C.B., Wong, I.G., Scotti, O., and Wentworth, C., 1987, New evidence on the state of stress of the San Andreas fault system: Science, v. 238, p. 1105–1111, doi: 10.1126/science.238.4830.1105.

Printed in USA