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Retrospective on “Low-angle (denudation) faults, hinterland of the Sevier orogenic belt, eastern Nevada and western Utah” by Richard Lee Armstrong

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The 1960s and early 1970s brought sweeping new syntheses of the Cordilleran orogen as having developed primarily in response to the motions of oceanic plates to the west. The main conclusions of these syntheses were that the Cordilleran miogeocline resulted from Neoproterozoic continental rifting; magmatic systems are a signature of subducting slabs beneath the continent; and variably oblique plate convergence was responsible for coastwise shearing and progressive accretion of large, sometimes far-traveled crustal fragments onto the continental margin through most of Phanerozoic time. The novelty of these concepts is clear from the pre-1960s literature, which contains only rare allusions to ideas that might be considered similar. Afterward, the nature of the debate illustrated their profound acceptance. Are the magmas arc or backarc? Was there just one Neoproterozoic rifting event? How far had the westernmost accreted blocks traveled? That none of these comparatively second-order issues are resolved after some three decades of research is humbling testimony to the progress represented by the early syntheses.

It is all the more surprising that out of an era focused on refining the role of plate tectonics in Cordilleran evolution, there emerged what may be the most “classical” of all concepts associated with the Cordilleran orogen, or at least, a tectonic element first discovered in the Cordillera and subsequently identified in every major orogen on the globe, namely, the geological signature of large-magnitude continental extension. Under rubrics such as “denudation faults,” “low-angle normal faults,” “detachment faults” and “Cordilleran metamorphic core complexes,” these features were initially regarded by most geologists as oddities. However, by the early 1990s analogous structures had been reported as fundamental tectonic elements of nearly every major orogenic system in the world (Alpine, Caledonian, Himalayan, Hercynian, Grenvillian, and many others) and of many passive margins and intracratonic rift systems (Burg and Chen, 1984; Lister et al., 1984, 1986; Wernicke, 1985; Seranne and Seguret, 1987; Selverstone, 1988; Zheng et al., 1988; Doblas and Oyarzun, 1989; Jolivet et al., 1990; Mezger et al., 1991; Hill et al., 1992; Mpodozis and Allmendinger, 1993). There was, and continues to be, much discussion regarding the implications of plate reconstructions on extensional tectonics in the Cordillera and elsewhere. But it is not the plate tectonic setting of extension that is the main “export” from the Cordillera to other orogenic systems, it is the structural expression of large-magnitude extension. Its discovery was not inspired by plate tectonics, but was instead the product of intense debate over geological field relations and the timing and nature of regional metamorphism.

That debate began in earnest in the late 1960s and early 1970s, at the same time plate tectonics was sweeping the globe. The debate was well articulated in a paper published in the Geological Society of America *Bulletin* in 1972 entitled “Low-angle (denudation) faults, hinterland of the Sevier orogenic belt, eastern Nevada and western Utah,” by Richard Lee Armstrong. Somewhat out of character, the paper contained no new data, but was mainly a series of simple line drawings of geologic maps from the “hinterland” of the east-vergent Mesozoic foreland fold and thrust belt in Utah. The structure of the hinterland was dominated by areally extensive low-angle faults developed within the thick, conformable Cordilleran miogeocline. In contrast to the thrust belt, these low-angle faults characteristically omit stratigraphic section, placing younger strata on older. In addition, the footwalls of the faults in a number of instances were metamorphosed to greenschist or amphibolite facies, suggesting that higher structural levels were emplaced on lower structural levels. The paper

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challenged the prevailing view, championed by Peter Misch of the University of Washington and Richard Hose of the U.S. Geological Survey, that the faulting was genetically related to the thrust belt to the east.

The Misch and Hose conceptions of the hinterland differed significantly. Misch and his students, who discovered the faults and contributed the bulk of their detailed mapping, viewed them as a direct expression of Mesozoic crustal shortening, more or less coeval with thrusting to the east (e.g., Misch, 1960). Stressing that the faults consistently omit section and are therefore normal faults, Hose and colleagues argued that they were the headward area of a huge gravity slide complex, the "toe" area of which was the thrust belt to the east (Hose and Danes, 1973).

The objective of Armstrong's paper was to demonstrate that the structures were related to upper crustal thinning (in agreement with Hose and colleagues), but were mainly Tertiary normal faults or local gravity slide blocks formed in response to Basin and Range faulting. He first plotted all known sub-Tertiary unconformities in the region on a map and showed that their depositional substrate was almost entirely Mississippian or younger. If widespread thrusting or attenuation had occurred in the Mesozoic, leading to what are now widespread exposures of Eocambrian through Devonian strata thousands of meters below the Mississippian, then unconformities between Tertiary strata and pre-Mississippian strata should be widespread. Using simple line drawings of geologic maps, he enumerated specific instances where geometrical and kinematic arguments indicated that the structures were almost certainly Tertiary. For example, a large normal fault in the southern Snake Range (Murphy Wash fault) was mapped as offsetting Tertiary strata on its south end and being truncated by the Snake Range decollement to the north, one of the most areally extensive low-angle faults in the hinterland.

One of the most instructive examples described was the northern Egan Range. There, entire sections of the miogeocline are tilted moderately to steeply westward and broken by low-angle faults with thousands of meters of stratigraphic throw. The pre-Tertiary strata are in contact with two outcrop areas of Tertiary volcanic strata, also moderately to steeply tilted to the west. The volcanic strata were mapped as unconformable on all surrounding rocks, but the map relations show both homoclines striking at a high angle into portions of the contact mapped as depositional. Armstrong (1972) showed in cross-section view (his Fig. 12) that subtracting the tilting of the Tertiary strata indicated that the faults were both normal and postvolcanic, not prevolcanic thrusts, as had been previously supposed.

The paper concluded with a general discussion of the role of hinterland structure in the evolution of the Cordilleran orogen, including a full-throated critical evaluation of the gravity sliding concept for the thrust belt—from which the concept never recovered.

Although a watershed paper on the basis of its ideas alone, the tone of the paper is almost singular in relating a contagious passion for the subject to the reader. Wernicke vividly remembers, as a second-year graduate student at MIT fresh from a summer mapping younger-on-older low-angle faults in Nevada as thrusts, cheering out loud as he read through it for the first time. Here, amid the mountain of bone-dry literature one must absorb to get up to speed in any field, was a lively, bare-knuckled intellectual attack, more in the classic American style of a Mencken or Twain essay than in the stupefying genre we as a community of scientific writers, referees, and editors work so hard to perfect.

In the review process for most major journals, and certainly the staid and conservative GSA *Bulletin*, authors are usually required to address referee and editor admonitions about "toning down" passages where the ideas of others are questioned, especially if they are widely held or "consensus" views. Avoid the first person. Keep references in parentheses. Talk about ideas, not people. Don't preach or patronize the reader! Avoid sarcasm or statements that, even unintentionally, might imply contempt or ridicule. Present interpretations and conclusions only at the end of the manuscript, after an unbiased rendering of facts has allowed the interpretation to "sell itself." In this paper, however, Armstrong would have none of it. The editor of the *Bulletin* at the time, Bennie W. Troxel, himself an early advocate of a Tertiary extensional origin for younger-on-older faults, wouldn't either.

Any decorum that might have been afforded through polite anonymity is crushed outright in the abstract: "Whitebread, Hose, Roberts and Crittenden advocate gravitational gliding models...," "Misch, Nelson, Fritz, Miller and Woodward..." relate the hinterland structures to Mesozoic compression, and "Armstrong, Burchfiel, Davis and Fleck..." argue they are unrelated to the thrust belt. The suspects were all in the lineup, and the curtain was drawn open.

The first paragraph of the text frankly states, "I believe that models linking denudation faults with thrust faults of Cretaceous age...are unlikely, and that the denudation faults are predominantly of Tertiary age and related to Basin and Range faulting" (Armstrong, 1972, p. 1729). In regard to interpreting a younger-on-older fault in the Wasatch Range as a thrust fault, he noted that it would require "a complex ad hoc explanation...," concluding that "Such gymnastics are unnecessary, and certainly not needed to explain the structures known to occur west of the Wasatch fault in this area" (Armstrong, 1972, p. 1734). After summarizing several mechanisms where thrusts might result in local younger-on-older structures, he concludes "None of these geometric mechanisms seems applicable to the hinterland structures. Geometric logic is a necessary prerequisite to any acceptable model for structural evolution" (Armstrong, 1972, p. 1735). In the following paragraph, the reader is informed that "Once popular and widely quoted compressional-thrust explanations for these ....features are falling out of favor" (p. 1736). At this point we're only 8 pages into a 26-page paper, and the jury has been led right on down to the gallows.

No gloves are donned for the descriptive body of the paper (Armstrong, 1972, p. 1734–1744). The basis for Misch's interpretation of a Cretaceous age for the Snake Range decollement is described as "unconformities below Cretaceous strata that lie more than 100 mi. away from the Snake Range" (p. 1736), whereas the author believes "evidence for dating the faults may be found in the southern Snake Range." After describing the Murphy Wash fault, he cites the conclusion of Lee et al. (1970) that the latest movement on the decollement was Tertiary, based on 20 Ma argon ages from cataclasites in the footwall, and simply concludes, "I agree wholeheartedly" (Armstrong, 1972, p. 1736).

As to map relations in the Deep Creek Mountains and near Gold Hill, it is stressed, following Mackin (and Hutton), that Tertiary strata are the guides to Tertiary deformation, and that "Casualness on this point has contributed much confusion to the literature concerning the eastern Great Basin" (Armstrong, 1972, p. 1738). After pointing out that a fault relationship on Harold Drewes's map of the southern Schell Creek Range is "a geometric impossibility—a fault displacement cannot change along strike by more than the distance along strike," he concludes, "To me, the simplest interpretation is that the 'thrust' and the Tertiary normal fault [that putatively cuts it] are one and the same feature..." (Armstrong, 1972, p. 1740, 1741).

The discussion of the northern Egan Range (Armstrong, 1972, p. 1741) begins, "An area where the structural significance of Tertiary volcanic rocks (Mackin, 1960) has been ignored is the northern Egan Range. Figure 11 shows the geology of part of the area mapped by Fritz (1960, 1968)," and, in discussing a contact mapped as depositional between Tertiary and Eocambrian that he reinterprets as a normal fault, he states "Such an interpretation is in agreement with the work of Adair (1961, and 1963, personal commun.) but denied by R. K. Hose (1971, personal commun.)" (p. 1741). Allowing that some structures in Fritz's map area could be Mesozoic, the Mesozoic thrust interpretation had nonetheless "been carried too far, and the Tertiary structures have been considerably underrated." The next sentence and paragraph begins, "Another example of proliferation of Mesozoic thrusts faults in violation of Mackin's principle occurs farther south, in the southern Egan Range, in an area mapped by Brokaw and Shawe (1965; Fig. 13)" (Armstrong, 1972, p. 1742); Brokaw and Shawe were also tried and convicted on grounds of geometric impossibility.

After reinterpreting several other "thrusts" (put in quotation marks no fewer than eight times from pages 1740 to 1743) and praising the conclusion by Moores et al. (1968) that many of the low-angle faults in the Grant and White Pine ranges were Tertiary denudation structures, he began the general discussion of the role of hinterland structure in the development of the Cordillera. Pages 1744–1747 in Armstrong (1972) constitute what is perhaps the most withering assault ever launched on a mainstream concept for Cordilleran evolution, not merely on account of rhetorical style, but in the clarity and persuasiveness of the arguments.

The discussion is prefaced with perhaps the best-known remark in the paper, which is something of a mantra among modern field geologists studying the problem of low-angle normal faults and similar phenomena. In the 1960s and 1970s, the "gravity slide" model of thin-skinned thrusting was advocated, and the compressional, "push-from-the-rear" model discredited, with the argument that it is mechanically impossible to push a thin sheet of rock from behind—only a body force acting on the entire thrust mass could allow it to remain coherent while overcoming frictional resistance along its base. Indeed, even today there is vigorous opposition to the existence of active low-angle normal faults on mechanistic grounds. Armstrong's position? "Arguments about mechanism are, for the most part, unsatisfactory and inconclusive, as they require knowledge we do not have on the large-scale behavior of rocks. I prefer to analyze what happened, geometrically and chronologically, rather than try to answer abstract questions of how it happened (mechanism and driving force). I am willing to grant anyone a process regardless that it may conflict with intuition or an evolving body of theory, if it can be proved to have happened" (Armstrong, 1972, p. 1745).

He went on to slay the gravity sliding dragon with abandon and flair. There is no possibility of a net downhill slope for the slide mass. Extension in the hinterland is insufficient to account for the minimum amount of shortening in the Sevier belt, without which "the glide model is untenable" (Armstrong, 1972, p. 1746). The thrust belt is continuous from Canada to southern California with major faults paralleling individual stratigraphic horizons for hundreds of kilometers. No feature of comparable stratigraphic and structural continuity is present behind the thrust belt, unless one supposes the level of gliding "jumps up and down stratigraphically to levels not observed in the presently exposed rocks (an ad hoc excuse to retain the tenability of the glide-decollement hypothesis)" (Armstrong, 1972, p. 1746). "An even more devastating argument..." is the provincialism of the Basin and Range denudation structures relative to the entire thrust belt. Gravity sliding "cannot be taken seriously" if it applies to only one segment of the thrust belt. "Further geometric difficulties..." are apparent in a regional cross section from the thrust belt to the Snake Range. "Alternate interpretations that have been proposed to date are in conflict with facts shown on geologic maps! Finally, I reject the glide-decollement models on chronological grounds" (Armstrong, 1972, p. 1747).

The concluding section begins by once again identifying the thrusters and gliders by name and dragging them around the block one last time prior to burial. Armstrong goes on to describe a generalized, large-scale cross section showing the thermal and structural state of the east half of the Cordillera (his Fig. 16) that few would take issue with today. It shows thinned crust under the miogeocline, ~100 km of compressional shortening and heating during the Mesozoic, and Tertiary extension of equal magnitude to the shortening to produce the thin crust of the modern Basin and Range. Contemporary ideas regarding the genesis of metamorphic core complexes and detachment systems have evolved far beyond this initial synthesis of denudation structures in the Sevier hinterland. But as in the case of the plate tectonic syntheses of the late 1960s and early 1970s, one can only be humbled in comparing the progress represented by defining the context of the hinterland structures in the Cordillera with that of subsequent refinements.

The significance and magnitude of Cenozoic extension in the Basin and Range province were generally underestimated at the time of Armstrong's 1972 paper, although Hamilton and Myers (1966) had argued for province-wide extension of as much as 100%. Documentation in the 1970s of highly distended arrays of steeply tilted fault blocks consisting largely of mid-Tertiary volcanic rocks (Anderson, 1971; Proffett, 1977) and additional areas of Tertiary low-angle normal faults that had uncovered mylonitic and metamorphic rocks (Davis, 1975; Compton et al., 1977) added support to the idea of large-magnitude Cenozoic extension and raised more questions about the age and significance of penetrative deformation. The association of low-angle normal faults and footwall mylonitic and metamorphic rocks, an association termed "metamorphic core complexes," was the focus of vigorous debate at a 1977 GSA Penrose conference (Coney, 1980a; Crittenden et al., 1980). The dragon of thrust tectonics in extensional guise that Armstrong (1972) sought to slay lived on in metamorphic core complexes as some conference participants insisted that Cenozoic low-angle normal faults were reactivated thrust faults on top of thrust-related mylonites (Drewes, 1977). Questions rather than answers took center stage because (1) some footwall-block deformation and metamorphism really were related to older thrust tectonics (Coney, 1980b); (2) shear-sense indicators in mylonitic rocks (Simpson and Schmid, 1983; Lister and Snoke, 1984) were not yet understood or had not been applied to metamorphic core complexes; and (3) isotope thermochronologic and geochronologic studies had not yet produced an overwhelming amount of high-quality data implicating mid-Tertiary mylonitization.

Metamorphic core complexes are characterized by a set of features that had not been identified in thrust belts, including well-lineated mylonitic fabrics overprinted by distributed brecciation and chloritic alteration, in turn overprinted by localized fault-related fracturing and crushing. Similar features were described in many thorough articles in GSA Memoir 153 (Crittenden et al., 1980), which provided a firm basis for the remarkable Cordilleran revelations that metamorphic core complexes were produced by progressive plastic to brittle deformation during exhumation and cooling of the footwall blocks of large low-angle normal faults (Davis et al., 1986), and that the normal faults accommodated crustal extension and resembled thrust faults in gross geometry (Wernicke, 1981). These insights, now applied around the world, were gained from a large amount of geologic field work in some of the most structurally complicated and lithologically diverse rocks in the Cordillera. Isotope thermochronologic and microstructural studies were instrumental in supporting this new model of extensional tectonism. Furthermore, the concept that thrust sheets are too thin and weak to push from behind and therefore must have been emplaced by gravity sliding was shown to be wrong, or at least unnecessary (Dahlen, 1984), which eliminated one of the original rationales for seeking synthrusting extensional structures and denuded areas in the hinterland of thrust belts. By the late 1980s, the dragon of thrust tectonics in extensional guise that Armstrong wounded so badly had been largely laid to rest.

Low-angle normal faults and metamorphic core complexes were only locally disentangled from thrust faults and areas of crustal thickening, as regionally they are clearly associated. Crustal thickening and associated surface-elevation increase and Moho depression increases crustal gravitational potential energy, and this energy is released by extension and crustal thinning (Molnar and Lyon-Caen, 1988). Greater crustal thickening should therefore be capable of driving greater extension. Metamorphic core complexes have been interpreted as products of unusually large magnitude extension that occurred where earlier crustal thickening had been unusually great (Coney and Harms, 1984). It has generally not been possible, however, to demonstrate that individual metamorphic core complexes correspond to local zones of greater crustal thickening except in the Harcuvar and Whipple complexes in the lower Colorado River trough (Spencer and Reynolds, 1990), and the geologic factors responsible for the spotty distribution of metamorphic core complexes remain enigmatic.

As is typically the case with major scientific insights, the fallout is enough to keep many scientists busy for decades. The denuded footwalls of major low-angle normal faults, now known as "detachment faults," are commonly arched, and some are fluted and grooved, with wavelengths of kilometers to tens of kilometers (Rehrig and Reynolds, 1980; Frost, 1981). Arching along axes perpendicular to extension direction was attributed to isostatic uplift following tectonic denudation (Hyndman, 1980; Howard et al., 1982; Spencer, 1984). Soon after this insight it became apparent that detachment-fault footwalls must have had so little flexural strength during exhumation that the flaccid footwall block rose up from the mid-crust and filled in the space vacated by the laterally traveling hanging-wall block, much like water fills in the space behind a large, slow-moving ship (Buck, 1988; Wernicke and Axen, 1988; Spencer and Reynolds, 1991). Recognition of the fluid-like behavior of the mid-crust during detachment faulting and core complex uplift was a major new insight into extensional tectonic processes (e.g., Block and Royden, 1990; Wernicke, 1990, 1992).

The corrugated footwalls of submarine low-angle normal faults were recognized in the mid-1990s on the inside corners of ridge-transform intersections, a tectonic setting where magmatism is subdued and intermittent along slow-spreading ridges (Tucholke and Lin, 1994; Cann et al., 1997; Tucholke et al., 1998). Metamorphism, mylonitization, and hydrothermal alteration that affected some rocks dredged from below these corrugated surfaces appear to have occurred during progressive plastic to brittle deformation associated with tectonic exhumation and cooling, the same basic processes that produced Cordilleran metamorphic core complexes (Cannat et al., 1992; Jaroslow et al., 1996; Tucholke et al., 1998). The arched and corrugated surfaces probably consist largely of serpentinized peridotite extruded directly from beneath the adjacent mid-ocean ridge as part of the plate spreading process, and form new oceanic crust with little or no basalt and gabbro (e.g., Lagabrielle and Cannat, 1990).

Finally, Armstrong's disregard for assertions of physical impossibility is still tenable 25 year later when, with vastly more computational firepower and additional decades of analysis, geophysicists still can't agree on viable mechanical conditions for detachment-fault initiation (Wills and Buck, 1997) and movement (cf. Xiao et al., 1991, and Scott and Lister, 1992). Seismologists have also had difficulty accommodating low-angle normal faulting because so few first-motion determinations support low-angle slip (Jackson and White, 1989), although a few low-angle events have been detected (Abers, 1991), and their rarity may be related to the greater effectiveness of low-angle normal faults in accommodating crustal extension (Wernicke, 1995). In 1972 Dick Armstrong provided monumental insight into a line of inquiry in Cordilleran geology that, 25 years later, continues to yield insights into tectonic processes and lithospheric behavior around the world.

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