Lessons from a long-lived, complexly evolving extensional orogen along an active margin

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Extension in western North America has been ongoing locally since Eocene time, roughly 50 m.y. [*Axen et al.*, 1993; *Christiansen et al.*, 1992; *Wernicke*, 1992]. During nearly all of that time, the western margin of North America was an active margin, initially involving subduction of Farallon and Vancouver plates along the entire length [*Atwater*, 1970; *Atwater*, 1989; *Stock and Molnar*, 1988]. The belt of extended terranes is considerably longer than the modern-day Basin and Range province, reaching from southwestern Canada into central Mexico [*Henry and Aranda-Gomez*, 1992]. At about 29 Ma, the eastern corner of the Pacific plate came into contact with North America outboard of the actively extending part of the continent, and the margin began to evolve into a wrench/oblique rifting margin, lengthening through time gradually northward and in jumps southward [*Atwater*, 1970; *Atwater and Stock*, 1998; *Stock and Hodges*, 1989].

During the ~50 m.y. of Cenozoic extension in North America, there have been places that experienced as many as three episodes of extensional tectonism and others that have only been stretched once [*Axen et al.*, 1993]. In general, the extended regions correspond roughly with previously thickened regions, suggesting that thick crust and lithosphere left over from previous episodes of shortening played a critical role in driving extension [*Coney and Harms*, 1984; *Sonder et al.*, 1987], although there probably are exceptions to this generalization. In addition, extensional tectonism was generally synchronous with magmatism, but the validity of this generalization depends partly upon the scale of observation [*Axen et al.*, 1993].

The North American Cordillera is famous as the discovery place of large-displacement (tens of kilometers), mid-Tertiary low-angle normal faults, or detachment faults [*Anderson*, 1971; *Armstrong*, 1972; *Crittenden et al.*, 1980]. Most of these faults lie within a belt that runs from Canada to northwestern Mexico and that is narrower than the extended part of the Cordillera at any given latitude [*Axen et al.*, 1993]. Many, but by no means all, detachment faults evolved from low-angle normal-sense ductile-to-brittle shear zones that separate midcrustal crystalline "core" rocks from brittlely faulted upper-crustal basement and overlying strata of "Cordilleran metamorphic core complexes". Typically, these detachment faults formed in places that had not previously extended in Cenozoic time.

Subsequently, detachment faults have been recognized on all the continents (even within collisional orogens such as the European Alps and Himalaya) and in slow-spreading oceanic lithosphere, and have been dated from well back into Precambrian time to Quaternary, so they are not structures unique to the Cordillera nor to the mid-Tertiary.

Evidence that detachment faults of the western U.S. formed and slipped in low-angle (≤30°) orientations is well established. Particularly clear-cut examples include the Whipple-Chemehuevi [*Davis*, 1988; *Davis and Lister*, 1988; *John*, 1987; *Lister and Davis*, 1989, John, 1993 #725] core complexes and the Beaver Dam Mountains-Tule Springs Hills-Mormon Mountains region where low-angle normal faults do not involve lower plates showing significant metamorphism yet still cut into upper midcrustal levels [*Axen*, 1991; *Axen*, 1993; *Wernicke et al.*, 1985]. In fact, most detachment terrains are explained easily by low-angle normal slip, with other explanations generally requiring *ad hoc* rotations of the faults. This is not to say that some rotations of specific detachments during and/or after slip have not occurred. Favored means of rotation include domino-style tectonics [*Proffett*, 1977] on a crustal-scale [*Davis*, 1983], rolling hinge tectonics synchronous with detachment slip [*Axen and Bartley*, 1997; *Buck*, 1988; *Hamilton*, 1988; *Wernicke and Axen*, 1988], or subsequent tilting due to unrelated faults.

Domino-style fault arrays are relatively common in the upper plates of detachment faults in the Cordillera, along with steep normal faults and listric (upward-steepening, concave-up) normal faults. However, crustal-scale tilting of detachment-bounded domino-style arrays does not seem to be the rule.

Rolling hinge deformation related to detachment faults, in which the footwall uplifts isostatically as it is denuded of its hanging wall, is a common process [*Axen and Bartley*, 1997; *Hamilton*, 1988; *Spencer*, 1984, Buck, 1988 #9; *Wernicke and Axen*, 1988]. However, rotations accommodated by rolling hinge tectonics are generally only ~10° in well documented examples and it does not appear that rotations in excess of 10-20° are common during rolling hinge evolution [*Axen and Bartley*, 1997], so this does not provide a widely applicable escape from the existence of low-angle normal faults.

Enigmatically, detachment faults are the only major class of crustal scale faults that are nearly (some say totally) aseismic [*Jackson*, 1987; *Jackson and White*, 1989] although two possible low-angle normal earthquakes have recently been documented [*Abers*, 1991; *Abers et al.*, 1997] and geomorphic and geologic evidence exists for seismogenic low-angle faults in the Cordillera [*Axen et al.*, 1999; *Burchfiel et al.*, 1995; *Caskey et al.*, 1996]. This apparent lack of seismicity, combined with poorly understood mechanics, has led many Earth scientists to deny the existence of low-angle normal faults. It is worth noting, however, that the mechanical problems of low-angle normal faults are little different from those of high-angle reverse faults and the San Andreas fault (undoubtedly the most well studied major fault in the world), implying that our basic understanding of the mechanics of all faulting has room for considerable improvement.

The principal remaining conundrum that is specific to low-angle normal faults seems to be their low levels of seismicity. Theories to explain this (apart from denial of the existence of low-angle normal faults) include aseismic creep [*Jackson*, 1987], infrequent earthquakes of abnormally large magnitude [*Wernicke*, 1995], and triggering by other seismic events of noncontroversial nature that may disguise the seismic signal related to low-angle normal slip [*Axen*, 2000 (in press); *Caskey and Wesnousky*, 1997].

The mechanics of low-angle normal faults do not fit well with the combination of Andersonian and Mohr-Coulomb mechanics, which predicts that normal faults should be steep [*Anderson*, 1942]. Most suggested solutions to this problem can be grouped into two types: those that attempt to explain slip and/or formation at low angles through rotations of the stress field [*Spencer and Chase*, 1989; *Yin*, 1989] and those that explain slip and/or formation via fault weakness due to elevated pore-fluid pressure and anisotropy imparted by the older mylonitic foliation [*Axen*, 1992; *Bartley and Glazner*, 1985; *Bruhn et al.*, 1982]. Stress-field models that give sufficient stress-field rotations may not yield resolved shear stress on low-angle planes sufficient to drive slip however [*Wills and Buck*, 1997]. High fluid pressure within detachment zones might tend to hydrofracture the upper plate [*Guth et al.*, 1982] so some method to prevent this is required. *Axen* [1992] used stress compatibility arguments [*Rice*, 1992] to "solve" this problem. On the basis of field evidence from the Whipple Mountains, it has been argued that detachment faults are neither weak nor subject to anomalously high pore pressure, but slip because they follow a different failure criterion (noncohesive friction) than that of their surroundings (cohesive Mohr-Coulomb failure) [*Axen and Selverstone*, 1994].

In spite of the fact that detachment faults clearly accommodate regional extension and thinning of the crust, there are good reasons to believe that the metamorphic cores themselves thickened during detachment activity either by influx of magmas localized there [*Gans*, 1987; *Miller et al.*, 1983; *Reynolds and Rehrig*, 1980] or by flow of a fluid crustal layer [*Block and Royden*, 1990; *Wdowinski and Axen*, 1992; *Wernicke*, 1990; *Wernicke*, 1992]. This is required to explain the anomalously high local elevations of domal metamorphic cores, although cores are not anomalously high relative to unextended terrains surrounding the core complex belt.

In spite of having accomplished extension across parts of the Cordillera amounting to ~250 km [*Hamilton and Myers*, 1966; *Wernicke et al.*, 1988], final rifting of the continent in the Gulf of California did not follow the belt of metamorphic core complexes but occurred instead along the axis of a previously developed but relatively short-lived volcanic arc adjacent to a strong crustal "beam" formed by the Peninsular Ranges batholith [*Stock and Hodges*, 1989]. Although the early gulf extension direction was roughly orthogonal to the rift trend [*Angelier et al.*, 1981; *Umhoefer and Stone*, 1996], the rifting that finally sundered the lithosphere was strongly oblique to the rift margin and involved strain partitioned among local and regional normal faults, strike-slip faults, vertical-axis rotations, incipient spreading centers and oceanic spreading [*Axen and Fletcher*, 1998; *Lee et al.*, 1996; *Lewis and Stock*, 1998; *Lonsdale*, 1989; *Stock and Hodges*, 1989; *Stock and Hodges*, 1990; *Umhoefer and Stone*, 1996]. Interestingly, low-angle normal faults related to this episode of rifting are relatively uncommon on the exposed margins [*Axen and Fletcher*, 1998], although more may be submerged within the Gulf.

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