Fault-bend fold

Suppe, 1983
Fault-bend fold

Suppe, 1983
Advantages:
   Can be reconstructed from surface geology
Assumptions:
   Pervasive slip on bedding planes as rocks pass through hinges
   Slip is carried off-section (no deformation of lower plate)

Suppe, 1983
Fault-Propagation fold

Namson and Davis, GSA Bull, 1988 after Suppe and Medwedeff, 1984
Fig. 24. Structural interpretation of the Nanliao anticline, southern Taiwan (modified from Suppe, 1980b).

Suppe, 1983
Coalinga anticline grew in the earthquake, which lacked any surface faulting.
Fig. Narrows Verdes Inglewood Pliocene-Quaternary WG, Wilmington fault; Huntington RH, Mountains; SM, Santa anticlinorium; SMF, Santa 1971 1965; LF, Lopez Jennings the pattern, anticlinorium; fault; cross fault. San Fernando (Mw=6.6) Fernando SGF, San SR, Santa and 0 • graben; fault; fault; fold basement. locations MW earthquake the magnitude 1969]. are WSGM, western [modified map and lines, PVF, Palos Angeles; LA, Los Boulevard Hills; fault. LA, Los Cienegas Hills; fault. WF, Whittier fault; the LCF, Las Cienegas CF, Compton Yerkes al., I 1987 I I 1984; Jennings the magnitude 1987 earthquake. No significant similarity exists for the geometry of the Miocene and deeper trends. To determine the origin of the Miocene anticlinoria, which are mainly continuous and downthrown on the west, observed data offer unique insights. This is a viable approach to testing hypotheses of the origin of the folds. This is a viable approach to testing hypotheses of the origin of the folds. This is a viable approach to testing hypotheses of the origin of the folds. This is a viable approach to testing hypotheses of the origin of the folds. Because Davis et al., JGR, 1989 offers data that demonstrates the significant role of Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocene Miocen
Inbal et al. got lots of small EQs from a very dense array and see the Newport–Inglewood fault extending into the mantle, not detached as thought by Davis et al. This helps reveal a weakness of the geometric reconstructions of fold belts: they need detachment to go off the edge of the model at the side.
Well, as a prelude to the Laramide, let’s discuss a different flavor of this: basement cored folds.
Figure 5. A comparison of interpretations of the Soda Lakes area, Colorado, utilizing the upthrust model (a) modified from Osterwald (1961), and the fold-thrust model (b) modified from Berg (1962a). Comparison of bed-length measurements of the Dakota Sandstones (Kd) and the top of the Precambrian basement between reference lines (W-X), (Y-Z), indicates the upthrust model (c) is out of structural balance by approximately 20 percent, whereas the fold-thrust model (d) is balanced to less than 5 percent error (after Brown, 1987).
Brown, GSA Mem 171, 1988

Rattlesnake Mtn interpretation of Sterns, 1971

Brown, GSA Mem 171, 1988
Rattlesnake Mtn
interpretation of
Brown, 1984

Rattlesnake Mtn
interpretation of
Sterns, 1971

Brown, GSA Mem 171, 1988
Brown, GSA Mem 171, 1988

Rattlesnake Mtn interpretation of Brown, 1984

Rattlesnake Mtn interpretation of Sterns, 1971

Rattlesnake Mtn interpretation of Brown, 1984

A. Rattlesnake Mtn., Wyoming

B. Fault Dip Calculation

\[ H = \left( BC + \frac{AC}{2} \right) \sin \Delta \]

\[ S = \frac{AB + AH - (BC + AC/2) (1 - \cos \Delta)}{} \]

Fault Dip Relative to Footwall = arctan \( H/2S \)

Erslev, Geology, 1986
Figure 1. Models of fault-propagation folds. A: Geometric kink-band model (Suppe and Medwedeff, 1984). B, C, D: Analog experimental models of folds above thrust (B; Chester et al., 1988), reverse (C; Friedman et al., 1980), and normal (D; Withjack et al., 1990) faults.
Figure 2. Geometric end members of triangular shear-zone folding. Erslev, 1991
Figure 3. Simple shear and trishear approximations of homogeneous shear in triangular shear zones.

Erslev, 1991
Advantages:
Deals with more realistic geometries in foreland situations than fault-bend folds

Disadvantages:
Requires plastic deformation in trishear zone, which can become non-unique in terms of structures

Erslev, 1991

Figure 4. TRISHEAR-generated, homogeneous and heterogeneous fault-propagation folding above (A) thrust (30° dip, 60° apex angle), (B) reverse (90° dip, 60° apex angle), and (C) normal (60° dip, 40° apex angle) faults.

Figure 5. Fault-propagation trajectories suggested by homogeneous, footwall-fixed trishear in front of thrust faults (45° dip, 60° apex angle).

Erslev, 1991
Fig. 1. Proposed structural styles for the Wind River fault. Structure between that in Figure lc and in le is representative of the fault at depth; x-x represents the position of the present ground surface.

Smithson et al. JGR, 1979
Figure 3. Unmigrated 24-fold CDP stacked reflection profile representing the upper portion of the Wind River thrust. Arrows define the position of the events representing reflections from the thrust plane. A = reflections from shallow sediments of Green River Basin. C = split (in line sections) of clasticimentary reflections under fault with no evidence of overturning. D = position of thrust against base of sediments. E = thrust reflection in the Precambrian crystalline rocks of the crust.
Figure 4. Interpretation of events seen on all three OCEMP profiles. There is an overlap from the top northeast to bottom southwest parts of the diagrams. The position of the Wind River thrust at the surface is represented by a line. The profiles were recorded in 200 two-way milliseconds. Dashed events represent diffractions or off-lens reflections. A = reflections from underlying sediments of the Green River Basin. B = uplift (in time sections) of sediments underlying the Pecos River thrust over them by the Wind River thrust. C = termination of ordinary layers against thrust with no evidence of overturning. E = appearance of thrust in the Pecos River crystalline rocks of the coast. Dotted lines represent synthetic low-frequency events.

Figure 5. Bouger gravity anomalies and calculated models. Horizontal and vertical scale is in kilometers. T = thickness of layers in kilometers; ρ = density in g/cm³. Continuous line represents channeled gravity. Dots represent estimated gravity.
Figure 4. Illustration of congruency between seismic reflection data on Wind River thrust, Wyoming, and structural modeling discussed in text.
Other shortening estimates: 60-120 km by Chapin and Cather (1983) to NNE
43-52 km to ENE (Bird, 1998)
Figure 12. True-scale cross sections of the Precambrian basement surface in Wyoming (after Blackstone, 1990a) on lines shown in Figure 2A. These sections assume delamination in the lower crust and a uniform crust-mantle interface at 40 km below sea level. All fault geometries in the lower crust are schematic yet restorable in concept.
Figure 5. Map and rose diagrams of LAR arches, faults, and folds in Wyoming, Colorado-Utah, and New Mexico-Arizona.

Erslev, & Koeng, GSA Mem 204, 2009
Laramide thrusts are underrepresented by surface fault data because thrust faults commonly go blind by fully transferring their slip into folding and cryptic layer-parallel slip. For example, exposed faults in the NE Bighorn Basin are mostly small, E- to NE-striking, high-angle faults, not the large, NNW-striking blind thrusts that dominate fault slip at the basement level (Stanton and Erslev, 2004). In addition, LAR arch and fold data sets include fewer post-Laramide structures because post-Laramide extension was dominated by faulting, not folding. Thus, we interpret the overall Laramide GIS and minor fault data sets as indicating ENE-WSW (N66-67E–S66-67W) shortening and compression during the Laramide orogeny.

Hypotheses invoking multidirectional deformation, either due to multiple stages of differently oriented compression (Chapin and Cather, 1981; Gries, 1983, 1990) or due to pervasive multidirectional structural weaknesses (Marshak et al., 2000; Timmons et al., 2001), predict that Laramide structures should be systematically multimodal. This is not supported by regional minor fault or LAR fold data, which show dominantly unimodal distributions (Figs. 1, 3G, and 5). The LAR arch rose diagram (Fig. 3F) is multimodal, but non-NNW-SSE arches are geographically restricted—N-S arches largely come from New Mexico–Arizona, and E-W arches largely come from Wyoming, where they follow major Precambrian zones of weakness. However, rose diagrams of LAR faults (Figs. 3G and 5) can be interpreted as showing NNW-SSE and N-S modes, consistent with the previous hypotheses.

To further test the possibility of multimodal structural trends of regional extent, LAR fault and fold rose diagrams were created on a 75 km grid with a 75 km radius of analysis (Figs. 10 and 11). These rose diagrams show that N-S petals come mostly from eastern subsets, NNW-SSE petals come mostly from western subsets, and relatively few local rose diagrams are truly bimodal. Thus, indications of multidirectional Laramide deformation appear to result from the combination of local unimodal domains, not regionally pervasive bimodal distributions.

To aid in visualizing regional patterns, fault (Fig. 10) and fold (Fig. 11) orientations were subdivided into six distinct domains based on LAR fold (primarily) and fault orientations: (1) Wyoming, (2) Green River Basin, (3) Uinta Mountain, (4) Colorado, (5) Colorado Plateau, and (6) New Mexico (Fig. 12; Table 5). The Green River Basin, Uinta Mountain, and Colorado Plateau domain boundaries occur where changes in fold rose diagrams correspond with major structural boundaries. The Colorado domain, which contains the northeastern corner of the Colorado Plateau, captures the systematic change in fold orientations across Colorado in a single domain. The Wyoming domain was differentiated from the Colorado domain due to changes in fault patterns at the Colorado-Wyoming border. The multimodality of LAR Fault-Strike Orientations

![LAR Fault-Strike Orientations](A)

![LAR Fold-Axis Orientations](B)

Figure 9. Histograms for all digitized LAR faults and folds from 0° to 180° in 5° increments.