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The power of integration: combining paleomagnetic data with structural analysis to better understand the kinematics and mechanics of complex orogens

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Abstract: Reconstructing the kinematic evolution, and understanding the mechanical processes of orogenic curvature are two long standing questions within the structural geology and tectonics community. At the roots of these questions are when and how orogens acquire curvature relative to their protracted deformation histories. A complete kinematic model for orogenic systems is described by the temporal evolution of its three-dimensional displacement field, comprised of bulk translation, horizontal- and vertical-axis rotations, and internal strain. The best way to quantify vertical-axis rotation is through paleomagnetic analysis done at appropriate scales. Paleomagnetic studies provide a key dataset for testing kinematic models that predict different spatial and temporal distributions of rotations related to orogenic curvature. For a model to be valid, however, it must agree with strain and structural data, and when integrated can illuminate the mechanisms responsible for orogenic curvature and critical-wedge dynamics. To highlight this point, a case study from the Wyoming salient in the Sevier fold-thrust belt is presented. This study incorporates paleomagnetic, anisotropy of magnetic susceptibility, strain and mesoscopic structure data to develop models for orogenic evolution.

Keywords: paleomagnetism, orocline, Wyoming salient, fold-thrust belt, strain, vertical-axis rotation.

The complete kinematic model for a curved orogenic system is described by the temporal evolution of its three-dimensional displacement field, comprised of bulk translation (related to slip on major faults), horizontal- and vertical-axis rotations (produced by large-scale folds and motion of coherent blocks), and internal strain (accommodated by cleavage, vein and fracture networks, minor folds, minor faults, and grain-scale fabrics). Traditionally, the displacement field of fold-thrust belts is evaluated from cross sections that only incorporate map-scale faults and folds (e.g. Dahlstrom, 1969). Contributions from internal strain and vertical-axis rotations are generally not included due to difficulty acquiring these data at appropriate spatial resolution. Failure to incorporate internal strain and vertical-axis rotation data, however, can greatly affect accuracy of fold-thrust belt restorations and consequently our understanding of wedge mechanics (e.g. Mitra, 1994; Sussman, 2002). Only by integrating paleomagnetic and detailed structural studies can the complex development of curved orogens be adequately deciphered (Gray and Stamatakos, 1997; Hindle and Burkhard, 1999).

Various kinematic models have been proposed to explain macroscopic-scale curvature in mountain belts: 1) uniform translation of a primary arc with no subsequent rotation (e.g. Eldredge *et al.*, 1985), 2) radial spreading of a primary arc with no subsequent rotation (e.g. Crosby, 1969), 3) differential shortening with parallel thrust slip that produces progressive curvature (e.g. Gwinn, 1968), 4) divergent thrust emplacement with curved slip that produces progressive curvature (e.g. Hindle and Burkhard, 1999), 5) wrenching along localized strike slip zones (e.g. Beutner, 1977), and 6) superimposed oroclinal bending of originally linear fold-thrust belts (e.g. Carey, 1955). Each of these models predicts distinct rotation and strain patterns that can be tested with adequate spatial distribution of data across and along orogen strike.

This article highlights the power of integrating paleomagnetic and structural data for constructing viable four-dimensional models of fold-thrust belt evolution. The presented case study comes from the Sevier fold-thrust belt in North America.

Geological setting

The Sevier orogenic belt lies along the eastern margin of the North American Cordillera, and is characterized by folds and thrust faults that shortened and translated miogeoclinal rocks overall eastward toward the craton during the Early Cretaceous to Early Tertiary (Armstrong and Oriel, 1965). The belt is divided into a number of salients (Lawton *et al.*, 1994), including the Wyoming salient, which is bound to the north and south by the basement-cored Gros Ventre and Uinta foreland uplifts (Fig. 1). Major thrusts and associated folds display curvature over a range of scales, with regional structural trends curving from NW in the northern part to NE in the southern part of the salient, combined with local curvature near oblique thrust ramps, transfer zones, and along some fold systems. Greatest curvature occurs near the salient ends, whereas the central part trends N-S with slight curvature only. The orogenic wedge propagated progressively eastward toward the foreland, with development of the middle Cretaceous Crawford, mostly Late Cretaceous Absaroka, and Early Tertiary Hogsback systems (DeCelles, 1994).

Thrust sheets in the Wyoming salient display systematic suites of mesoscopic and microscopic structures that produce distinct patterns of internal strain. Thrust sheets experienced widespread early layer-parallel shortening (LPS) and minor strike-parallel extension. Regionally, shortening directions display a radial pattern, remaining subperpendicular to structural trend around the salient, in all thrust sheets.

Vertical-axis rotations have been estimated from previous paleomagnetic and structural studies in specific parts of the Wyoming salient; however, these studies have interpreted inconsistent patterns. Grubbs and Van der Voo (1976) reported significant vertical-axis rotations (up to 60º) for pre-folding magnetizations in Triassic strata in the northern portion of the salient, possibly related to buttressing by the Gros Ventre foreland uplift. On the other hand, McWhinnie *et al.* (1990) interpreted syn-folding remagnetizations in Jurassic strata to indicate no significant vertical-axis rotations in the same general area. Schwartz and Van der Voo (1984) reported little to no rotation in Jurassic rocks from part of the Absaroka thrust sheet, whereas Craddock *et al.* (1988) interpreted curved deformation paths and moderate vertical-axis rotations in this area based on systematic changes in orientations of calcite twin strains. Thus, rotations likely occurred in some areas, but contradictions exist in interpretations, partly related to limited sampling. Here we resolve such contradictions by integrating systematic paleomagnetic studies with detailed structural analysis to accurately determine rotation patterns within the Wyoming salient.

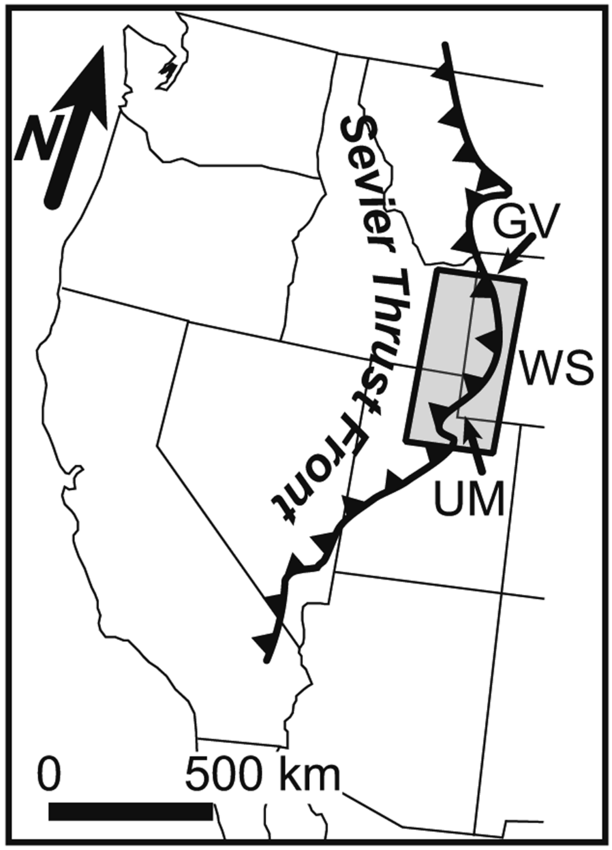

Figure 1. General location map of the Sevier thrust-belt, North America. Inset black box shows location of the Wyoming salient (GV – Gros Ventre uplift; UM – Uinta Mountain uplift).

Methods

A total of 155 sites were collected in redbeds of the Triassic Ankareh formation. The formation consists mostly of red, quartzose to subarkosic, variably micaceous to calcareous sandstone and mudstone. A conglomeratic interval is locally present, and divides Ankareh into an Early Triassic lower part, and a Late Triassic upper part (High and Picard, 1969). Sampling was designed to optimize the distribution of sites along strike in order to delineate regional rotation patterns of individual thrust sheets, with several detailed sampling arrays designed to check for local variations associated with folds and oblique ramps. Paleomagnetic 'field' tests (e.g. fold tests) were performed on site data to establish the age of remanence acquisition, which is critical for evaluating the validity of paleomagnetically derived rotations. Detailed structural data were also collected at each site, including orientations of bedding, cleavage, fracture sets and veins, as well as minor fault slip data where possible. For sites containing adequate numbers of reduction spots, strain was estimated using reduction spot shape fabrics. Anisotropy of magnetic susceptibility (AMS) measurements were also run for paleomagnetic cores to determine the distribution and geometry of internal magnetic fabrics and their relationship to finite strain.

Results of paleomagnetic analysis

Red beds sampled for this study contain two ancient magnetic components: 1) a near-primary Triassic remanence (Tr) carried by hematite, and 2) a Cretaceous chemical remagnetization (K) carried by both magnetite and hematite. Both the Tr and K components have medium to high unblocking temperatures and well-defined thermal demagnetization behavior that decays linearly to the origin. The Tr component displays both normal and reverse polarity. The K component only displays normal polarity. Of the 155 sites, 80 carry the Tr component, 26 carry the K component, 6 carry both the Tr and K components, and 9 carry a strong recent viscous overprint. Of the remaining 34 sites, 26 had unacceptably high dispersion with α_{95} >15°, and 8 had no interpretable results.

In situ site mean directions for both Tr and K components display a high degree of scatter, suggesting significant amounts of local rotation and tilt subsequent to magnetization acquisition. Due to the complex nature of deformation in the Wyoming salient, special care was taken in restoring *in situ* site means to remove any spurious vertical-axis rotation related to tilting. Restored orientations were estimated by progressively untilting bedding to horizontal, using suc-

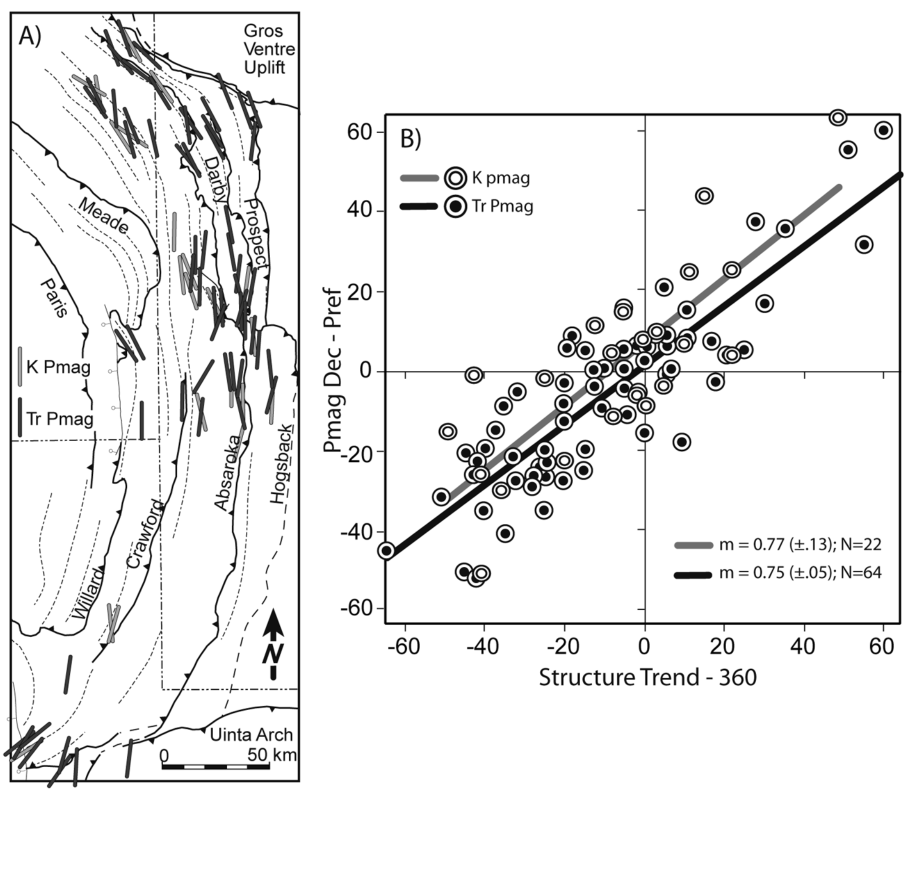

Figure 2. A) Relative rotations for Tr (dark grey bars) and K (white bars) component site means showing systematic variations around the salient with respect to reference directions. In each case, the structurally corrected site mean is plotted with respect to appropriate reference direction (340/350 degrees for Lower/Upper Triassic and 350 degrees for Cretaceous component). Note that similar rotation patterns are apparent in all of the studied thrust systems, B) weighted least-squares strike tests for the Tr and K components. m = best-fit slope with 1σ confidence intervals (in parentheses); N = total number of sites. Structural trend estimated from ~1 km scale geological map relations.

cessive rotations based on structural relations (including fold plunge and removal of younger block rotations related to Cenozoic extension and Laramide basement uplift). Restored site means display less scatter, with typical inclinations of 0 to 20° for the Tr component and 50 to 70° for the K component, although both components still show variable declination related to vertical-axis rotation.

Because rotation patterns may have varied spatially and temporally within the Wyoming salient, tilt tests were conducted where data permitted for 9 structural domains. Restored Tr components were gently inclined for all sites, consistent with the Triassic paleolattitude of North America. Maximum clustering of Tr site means occurred near 100% unfolding for most domains. However, because Tr site means were at generally low angles to local fold axes, unfolding generally resulted in only minor changes in site mean directions and clustering. Based on paleomagnetic poles for North America (Molina Garza *et al.*, 1998; Steiner and Lucas, 2000 and references therein), a reference (non-rotated) declination of 340° was used for Early Triassic sites, and a declination of 350° was used for Late Triassic sites in the salient. Tilt tests for the K component indicated an early syn-folding magnetization, with maximum clustering at 80-90% unfolding. The K component carries only normal polarity, consistent with acquisition during chron C34, lasting from 121-83 Ma (Cande and Kent, 1995), and appears related to a regional hydrothermal event (Burtner and Nigrini, 1994). The K component was likely acquired at ~100 Ma, during which time the paleopole for North America was relatively stationary, with a reference declination of 350° for the salient.

Restored declinations for Tr and K component site means display systematic variations around the salient with respect to the reference directions (Fig. 2a). Declinations in the northern part of the salient are rotated about 20 to 30° counterclockwise for most sites, with locally greater rotations. Declinations in the central part of the salient only record minor rotations. Declinations in the southern part of the salient record clockwise rotations. Importantly, similar rotation patterns are apparent in all of the studied thrust systems. In detail, restored declinations typically display minor (approximately ±10°) scatter for sites in similar structural domains, partly related to measurement uncertainties, and to local structural noise from non-systematic, small-scale block rotations. Restored declinations locally show greater scatter (>20° for a few sites) in overturned fold limbs that may have more complex deformation histories. Restored declinations for 2 sites from the adjacent Gros Ventre and Uinta foreland uplifts, however, do not show significant rotation (Fig. 2a), indicating rotation was spatially confined to the salient and associated with Cretaceous to Early Tertiary thrusting.

Correlation between vertical-axis rotations (estimated from differences between restored paleomagnetic declination and corresponding reference directions) and changes in large-scale structural trend around the salient are quantitatively evaluated using a modified weighted least-squares paleomagnetic strike test (Yonkee and Weil, 2010a). The Ankareh formation had 86 sites that carried the Tr component, with 67 sites located in relatively simple structural settings: 17 sites from overturned fold limbs and oblique ramps, and 2 sites from adjacent foreland uplifts. Linear regression of the 67 *filtered* sites yielded a best-fit line with a slope of 0.75, and a 1 confidence interval of ±0.05 (Fig. 2b). The Ankareh formation had 32 sites that carried the K component, with 22 sites located in relatively simple structural settings, and 10 sites from overturned fold limbs and oblique ramps. Linear regression of the 22 *filtered* K sites gave a slope of 0.77, and a 1σ confidence interval of ±0.13 (Fig. 2b). Residuals had an approximately normal distribution, were uncorrelated with structural trend, and gave an acceptable goodness of fit. The calculated slopes indicate that ~3/4 of final salient curvature resulted from regionally systematic secondary rotation, with ~1/4 related to primary curvature prior to large-scale folding and thrusting.

Understanding local complications is important in evaluating scatter in regional rotation patterns and in developing 3D restorations. Areas with locally oblique structural trends generally experienced tilting over gently to moderately dipping oblique ramps in underlying thrusts, with limited vertical-axis rotations superimposed on regional trends. This is similar to the findings of Weil (2006) for the Cantabrian-Asturian Arc of northern Spain, where sites located above local lateral and oblique ramps recorded only minor vertical-axis rotations, whereas sites collected regionally around curved fold and frontal ramp thrust traces recorded significant vertical-axis rotations. Sites near steeper ramps or tear faults in the Wyoming salient, however, had localized vertical-axis rotations, consistent with the kinematic model of Apotria (1992). Unusual rotation patterns also occur in transfer zones where out-of-sequence thrusts were superimposed on previously rotated blocks. Additionally, overturned fold limbs have locally anomalous patterns related to more concentrated, heterogeneous strain and small-scale rotations. By integrating detailed structural and paleomagnetic analysis, however, most local complications are understood (Weil *et al.*, 2010; Yonkee and Weil, 2010b).

Results of structural analysis

Mesoscopic structures, grain scale strain and magnetic fabrics also display regionally systematic patterns (Figs. 3a and 3b) (Weil and Yonkee, 2009; Yonkee and Weil, 2010b). Cleavage, tectonic stylolites and high-angle fracture sets in the Ankareh formation record widespread layer-parallel shortening (LPS) that largely preceded folding and thrusting in each thrust system. LPS directions are mostly subperpendicular to structural trends around the salient, defining a radial pattern (Fig. 3b). Cross-strike veins and conjugate tear faults record roughly strike-parallel extension over a protracted history. Extension directions estimated from veins are subparallel to structural trends and define a tangential pattern (Fig. 3a). Axial ratios of bed-parallel strain ellipses, estimated from reduction spots, record the magnitudes of LPS and extension. LPS intensity increases overall westward, from <5% shortening in much of the Hogsback sheet, to ~20% internal shortening in the Crawford sheet, and also toward the salient ends (Fig. 3b). Strike-parallel extension appears to be minor (~5%), with additional minor extension produced by conjugate tear faults oblique to structural trend and cross-strike veins. In detail, strain patterns are locally more complex near oblique ramps and at salient ends. Anisotropy of magnetic susceptibility (AMS) lineations, partly related to intersection of bedding and LPS fabrics, define a radial pattern, remaining subparallel to structural trend around the salient (Fig. 3a). AMS ellipsoid shapes display broadly similar patterns to corresponding strain data, with sedimentary and weak fabrics widespread in the eastern thrust systems, and stronger fabrics more common in the western Crawford thrust system and toward the salient ends. However, quantitative correlations

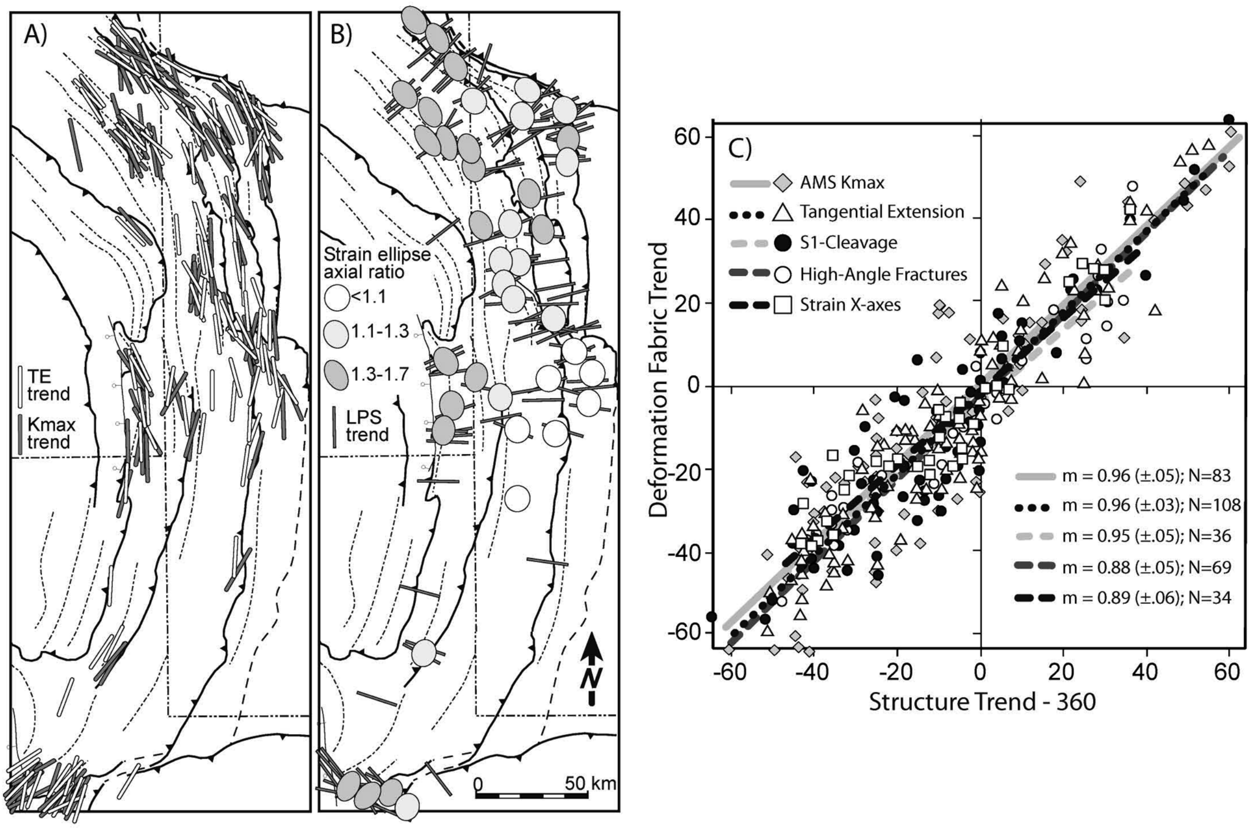

Figure 3. A) Orientations of tangential extension (TE – white bars) and magnetic lineations measured from AMS analysis (Kmax – dark grey bars) from Ankareh Fm sites collected in the Wyoming salient, B) orientations of LPS (dark grey bars) and 2D finite strain ellipses measured from Ankareh Fm sites collected in the Wyoming salient, C) weighted least-squares strike tests for AMS Kmax, TE, S1-cleavage intersection, high-angle fracture and strain X-axis orientations vs. regional structural trends. m = best-fit slope with 1 confidence intervals (in parentheses); N = total number of sites. Structural trend estimated from ~1 km scale geologic map relations.

between finite strain and AMS ellipsoid axial ratios are complex and include effects of varying lithology.

Strike tests of structural fabric orientations from cleavage, finite strain, high angle fracture sets, cross-strike veins, and AMS lineations yield respective slopes and 1σ confidence intervals of 0.89±0.06, 0.88±0.05, 0.95±0.05, 0.96±0.03, and 0.96±0.05, recording systematic regional patterns (Fig. 3c). Cleavage and finite strain that are most clearly related to early LPS have slopes of about 0.9, indicating that early shortening was close to, but not precisely perpendicular to large-scale structural trend.

Discussion

Paleomagnetic studies record two interpretable remanent magnetizations: a near primary Tr component and a K component acquired near the start of large-scale thrusting. Site means, restored for tilting, have declinations that systematically change around regionally curved structural trends, recording counterclockwise vertical-axis rotations in the NW-trending northern part of the salient and clockwise rotations in the NE-trending southern part of the salient (Fig. 2a). Similar rotational patterns for both the K and Tr components, combined with a lack of significant rotation in adjacent foreland uplifts, indicate that vertical-axis rotations were overall synchronous with large-scale thrusting. Deformation fabrics record early LPS, along with minor strike-parallel extension. Early LPS directions were about, but not exactly, perpendicular to large-scale structural trend. The amount of internal shortening increases overall toward more interior thrust sheets and toward the salient ends. Additionally, regional cross sections, offset piercing points, and detailed slip lineation data indicate that shortening decreases toward the salient ends and that slip directions are curved and slightly divergent around the salient.

General kinematic model for the Wyoming salient

Patterns of vertical-axis rotation, internal strain patterns, and large-scale structural relations are now integrated to constrain kinematic models. Based on paleomagnetic data (Fig. 2), end member kinematic models with little or no secondary rotation can be eliminated, including uniform translation of a primary arc and radial spreading. Presence of widespread, but minor (~5%) strike-parallel extension is also inconsistent with uniform translation, which predicts 0% extension, and radial spreading, which predicts major (>10%) extension. Timing and spatial relations of paleomagnetic data indicate that curvature developed during thrusting within the salient, which eliminates a model of superimposed oroclinal bending. When analyzed in an integrated framework, paleomagnetic, strain, and large-scale structural data indicate that the Wyoming salient is a progressive arc (Weil and Sussman, 2004). A composite model that combines ~1/4 primary curvature with ~3/4 progressive secondary curvature related to divergent emplacement along curved thrust slip paths and differential shortening is most consistent with observed paleomagnetic and strain patterns. In this model, thrusts initiate with slightly arcuate trends. Slip directions start parallel to early LPS directions and curve through an amount related to paleomagnetically estimated rotations. Most rotation occurs within the active thrust system near the leading edge of the orogenic wedge, with smaller amounts occurring during subsequent 'passive' transport of the wedge interior, as active deformation progressively shifts toward more frontal systems. This model matches observed rotation patterns, with slightly greater rotation of more interior sheets, minor tangential extension, and large-scale changes in fold-thrust shortening direction along orogenic strike. Note that more frontal systems start with slightly more circular, larger amplitude arcs, reflecting a combination of pre-thrusting sedimentary prism and syn-thrusting foreland basin geometry.

Inferences on mechanisms of orogenic curvature in the Wyoming salient

In the context of the above kinematic model, mechanisms responsible for evolution of curvature in the Wyoming salient can be evaluated. Two most sited mechanisms are: 1) "buttressing" by the Gros Ventre/Teton and Uinta basement highs, which pinned and rotated both ends of the frontal thrust sheets (e.g. Grubbs and Van der Voo, 1976), and 2) influence of initial sedimentary basin taper on geometry of individual thrust sheets (e.g. Boyer, 1995). These mechanisms are not mutually exclusive, and can be partly related to one another. Buttressing involves original promontories in the underlying basement that become sites of foreland uplifts. As the thrust wedge propagates into the foreland, additional translation is restricted by basement obstacles, which deflect stress trajectories, localize displacement gradients, and result in curved thrust fronts. Corresponding increases in initial sedimentary basin thickness between basement promontories also results in primary curvature, which becomes accentuated during thickening and propagation of the subsequent orogenic wedge. Using analog models, Marshak *et al.*

(1992) showed that initial sedimentary thickness strongly controls thrust spacing and initial frontal thrust position, with salient curvature partly controlled by along-strike variations in stratigraphic thickness. Another mechanism for developing curvature is along-strike differential shortening related to changes in wedge properties (e.g. Wilkerson, 1992). To produce significant curvature, however, this mechanism requires formation of large tear faults or other accommodation structures. Although small tear faults and local transfer zones are present in the Wyoming salient, this mechanism alone appears incapable of producing observed curvature.

Given the available kinematic data, the most likely mechanisms for curvature development in the Wyoming salient are variations in primary sedimentary basin and subsequent orogenic wedge thickness, and interaction with foreland uplifts that form along primary basement promontories (Fig. 4). Primary thickness variations result in slightly curved isopachs and associated lithological changes that influence thrust initiation and spacing (Figs. 4a and 4b). As the orogenic wedge grows during Cretaceous time, the initially thicker central part experiences greater shortening, forms higher topographic relief, and the thrust front propagates farther towards the foreland, with progressive rotation concentrated near the orogenic front (Fig. 4c). A combination of regional tectonic stress and stress induced from curved topographic slopes results in partly curved slip paths. Erosion of the wedge and deposition in a growing foredeep accentuates curvature of the sedimentary basin, which becomes progressively incorporated into the growing wedge. As the wedge propagates into the foreland during the Early Tertiary, it interacts with growing basement-cored uplifts along basement promontories at the salient ends, with additional localized rotation, wrenching and differential shortening (Fig. 4d).

Conclusions

The case study from the Wyoming salient highlights the power of quantifying vertical-axis rotations and internal strain patterns over a range of temporal and spatial scales to understand kinematic patterns and mechanisms that produce curved orogenic systems. Systematic paleomagnetic analysis done at appropriate spatial resolution is the best way to quantify vertical-axis rotations, and provides a key data set for testing kinematic models. However, vertical-axis rotation is just one component of the full three-dimensional dis-

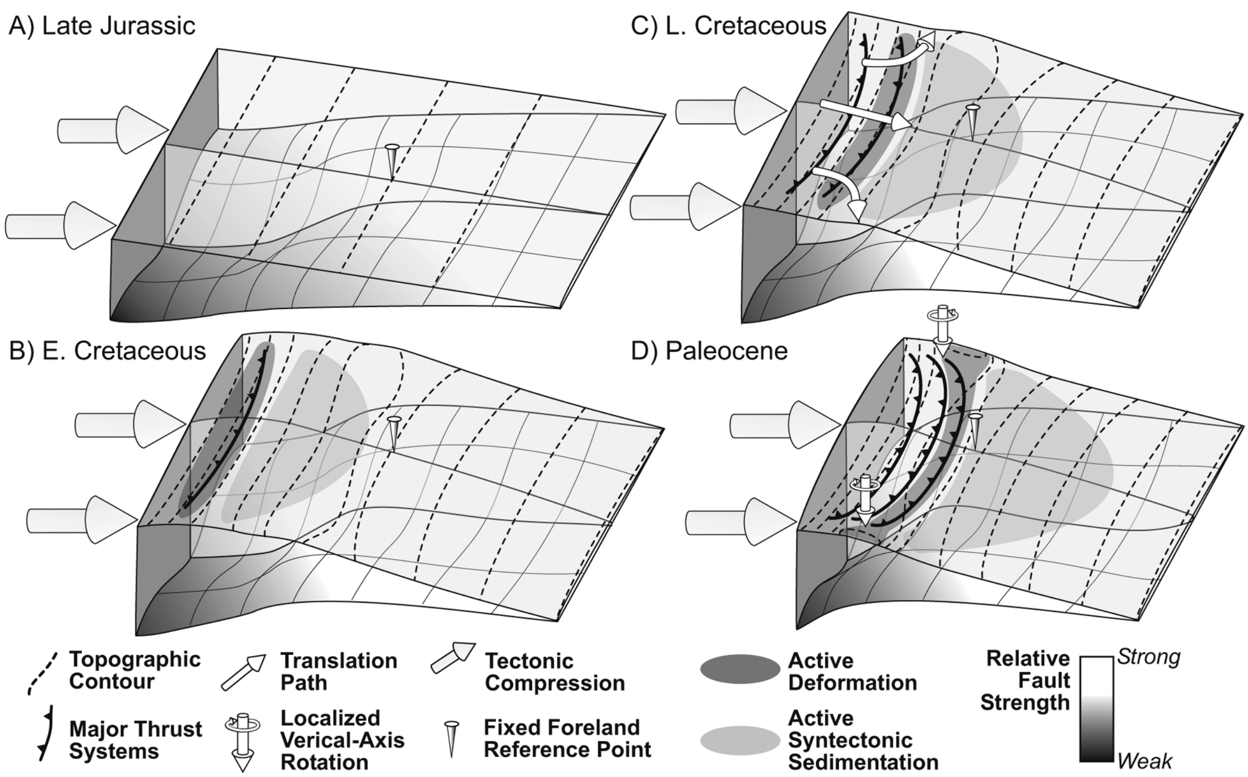

Figure 4. Block diagram of basic mechanical model for Wyoming salient wedge evolution.

placement field, and thus any viable kinematic model must also be consistent with available strain data. Accordingly, when developing models for orogenic evolution, multiple datasets should be integrated and statistically analyzed, incorporating data uncertainty, local structural noise and timing relations.

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