PERGAMON

Journal of Structural Geology 25 (2003) 1959–1972

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Fold axis-parallel rotation within the Laramide Derby Dome Fold, Wind River Basin, Wyoming, USA

John P. Craddock[a,*], Monica Relle[b]

[a]Geology Department, Macalester College, 1600 Grand Ave., St. Paul, MN 55105-1899, USA
[b]Department of Geology & Geophysics, University of Wisconsin, Madison, WI 53706, USA

Received 28 July 2000; received in revised form 22 October 2002; accepted 12 December 2002

Abstract

Derby Dome, a doubly plunging anticline (7 × 3 km) on the eastern flank of the Wind River Range, Wyoming, trends NW–SE in response to the regional NE–SW directed shortening of the Cretaceous–Eocene Laramide orogeny. Mesozoic sediments are exposed around the fold hinge above an east-dipping thrust fault that offsets Archean crystalline rocks at depth. Stress and strain ellipsoidal data were determined through the measurement of mechanically twinned calcite in limestones (Triassic Alcova through J–K Morrison Formation rocks; 13 samples), calcite cements (5 samples), and synfolding calcite veins (16 samples) around the northern half of the fold. On the outer limbs of the fold the maximum shortening strain axis (−3.5%, 15% NEVs) in the limestones and cements is sub-horizontal, layer-parallel and normal (NE–SW) to the fold hinge reflecting regional Sevier–Laramide shortening. This regional layer-parallel strain fabric is rotated into a fold axis-parallel orientation (NW–SE) near the fold hinge indicating that significant rotations occurred during folding. Synfolding calcite veins, of varying orientations, also preserve a local sub-horizontal, hinge-parallel shortening strain (−4.0%, 17% NEVs), suggesting that the regional Laramide stress and strain field was locally rotated into parallelism with the fold during shortening and displacement on the underlying thrust fault. In both the country rock, cement and vein data sets, the strain overprint noise (NEVs) increases toward the fold hinge. Inferred differential stress magnitudes are also higher for the vein calcite than for the country rock limestones or cements, and there is no interpretable pattern around the fold (avg. = 560 bars, range of 240–2000 bars). Fracture measurements ($n = 74$) in different lithologies have different orientations on each side of the adjacent Dallas Dome Fold suggesting layer-parallel rotation during folding, or active fracturing occurred uniquely on each fold limb.

Keywords: Fold axis-parallel rotation; Doubly plunging anticline; Derby Dome; Wind River Basin

1. Introduction

Mesozoic–early Cenozoic deformation of the western margin of North America is characterized by the formation of the Idaho–Wyoming fold-and-thrust belt (Armstrong and Oriel, 1965; Wiltschko and Dorr, 1983), the proximal Green River foreland basin (Dorr et al., 1977; Jordan, 1981), and the distal foreland basins and Laramide crystalline uplifts (Gries, 1983; Oldow et al., 1989). The older, thin-skinned Sevier portion of the deformation occurred near the margin with thrust translation directed eastward, whereas the younger, basement-involved Laramide uplifts and basins localized within continental North America reflect crustal shortening generally directed to the ENE related to docking and dextral translation of accreted terranes (see Gries, 1983; Bird, 1988) and probable reactivation of older basement faults (Marshak and Paulsen, 1996; Marshak et al., 2000). The Sevier shortening is preserved as a regional, E–W layer-parallel shortening (LPS) calcite strain fabric and is present as far east (>2000 km) as Minnesota in the Cretaceous Greenhorn Limestone (van der Pluijm et al., 1997). The LPS fabric in the autochthonous foreland is useful in understanding deformational rotations and translations in younger structures, specifically Laramide uplifts (Craddock, 1992; Craddock and van der Pluijm, 1999) where synorogenic calcite veins are present.

Derby Dome is a Laramide fold structure, cored by an east-dipping thrust on the eastern flank of the crystalline Wind River Range (Berg, 1962; Smithson et al., 1978; Steidtmann et al., 1983), and is part of a series of doubly-plunging en

* Corresponding author. Tel.: +1-612-696-6620; fax: +1-612-696-6432.
E-mail address: craddock@macalester.edu (J.P. Craddock).

0191-8141/03/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/S0191-8141(03)00035-X

échelon anticlines that are cored by basement (NW–SE; Keefer, 1970; Willis and Groshong, 1993). Mesozoic sediments exposed around the fold include the Alcova and Twin Creek Limestones, and calcite-cemented Nugget sandstone. These and numerous calcite veins allow for good sample coverage. Our goals were to: (1) analyze the rotation of the pre-folding Sevier LPS calcite strain fabric as Derby Dome folded and was breached by a thrust fault as the fold hinge overtightened (e.g. fault-propagation fold; Suppe, 1983); and (2) to observe the incremental stress-strain field preserved by twinned calcite in syn-folding veins. Our study of folding strains differs from previous fabric work on large-scale folds (e.g. Carter and Friedman, 1965) and outcrop-scale folds (e.g. Spang and Groshong, 1981; Hudleston and Tabor, 1988) in that we have pre-folding limestone and syn-folding calcite vein fabric data to interpret for a thick-skinned structure. This research is similar to that of Kilsdonk and Wiltschko (1988) for the thin-skinned Pine Mountain ramp-anticline limestones and synorogenic calcite veins.

2. Methods

2.1. Calcite twinning

Calcite twins mechanically at low differential stresses (~10 MPa; see Lacombe and Laurent, 1996; Ferrill, 1998), and is largely independent of temperature and normal stress magnitudes in the uppermost crust. Twinning is possible along three glide planes and calcite strain-hardens once twinned; further twinning is possible in a crystal along either of the remaining two e{0112} planes at higher stress levels, provided that stress is oriented >45° from the initial stress orientation (Teufel, 1980). The application of twinned calcite to structural and tectonic problems has been primarily restricted to studies of limestones (e.g. Groshong, 1975; Engelder, 1979; Spang and Groshong, 1981; Wiltschko et al., 1985; Craddock et al., 1993), calcite veins (e.g. Kilsdonk and Wiltschko, 1988), or, more rarely, marbles (e.g. Craddock et al., 1991). Craddock and Pearson (1994) and Craddock et al. (1997) have studied twinning strains in secondary calcite of basalts from DSDP Hole 433C and the Proterozoic Keweenaw rift, respectively. Rowe and Rutter (1990) and Burkhard (1993) have recently reviewed the variety of methods applied to utilizing twinned calcite in a host of geologic environments.

Paleostress (paleopiezometry of Engelder (1993)) responsible for twinning can be calculated in terms of their compressional (or tensile) orientation (Turner, 1953) and magnitude (Jamison and Spang, 1976; Rowe and Rutter, 1990). Strain ellipsoid axis orientations are computed using the calcite strain gage (Groshong, 1972, 1974) and are quite accurate for strains ranging from 1 to 17% (Groshong et al., 1984) although strain magnitudes vary greatly depending on lithology, grain size, porosity, etc., and are a function of twin thickness. Thin twins (~0.5 microns) are dominant in our sample suite, which is characteristic of calcite deformed below 200 °C (Ferrill, 1991, 1998). The calcite strain gage technique also computes positive and negative expected values (PEV and NEV, respectively) for all the twins in a given thin section. A NEV for a twinned grain indicates that this grain was unfavorably oriented relative to the stress field that caused the majority of the grains in a given thin section to twin. A high percentage of negative expected values (>40%) indicates that a second, non-coaxial twinning event occurred and these two twinning strains (PEV and NEV groups, respectively) can be analyzed separately (Teufel, 1980).

3. Results

3.1. Regional patterns of Western North America

Calcite strain results from limestones in the Idaho–Wyoming thrust belt preserve a layer-parallel, thrust transport-parallel twinning fabric that has been used to interpret dextral transpression associated with the progressive shortening and rotation within this thrust belt (Craddock, 1992) when compared with the same layer-parallel, E–W shortening fabric preserved in the autochthonous foreland as far east as Minnesota (Craddock and van der Pluijm, 1999). Synorogenic calcite veins across the thrust belt record high differential stresses and strain magnitudes (900 bars, −6%, respectively) in a variety of orientations, which reflect local complexities of piggyback thrusting rotations (Budai and Wiltschko, 1987; Craddock and van der Pluijm, 1988; see also Allmendinger, 1982; Kraig and Wiltschko, 1987; Apotria, 1990, 1995).

3.2. Laramide uplifts and basins

Forty-four calcite strain analyses from Paleozoic limestones and veins from the Beartooth, Wind River, Owl Creek, Bighorn and Black Hills Ranges (Craddock and van der Pluijm, 1999) compliment earlier, localized studies in the Bighorn Mountains (Hennings, 1986a,b; Carson, 1988), in the Teton-Gros Ventre Range (Craddock et al., 1988), and in the Wind River Range and Wind River Basin (Willis and Groshong, 1993). Calcite strain analyses from limestones in the Laramide uplifts preserve a regionally consistent ~ENE–WSW LPS fabric despite, in some cases, uplift and thrust transport from north to south (e.g. Owl Creek Range; Varga, 1993). Strain analyses from the folds flanking the Wind River Range (Willis and Groshong, 1993; 10 samples), including Derby Dome, record an E–W LPS fabric with some curious rotations (see below). Strain analyses of synorogenic calcite veins from a variety of Laramide uplifts record sub-horizontal, N–S shortening (Craddock and van der Pluijm, 1999).

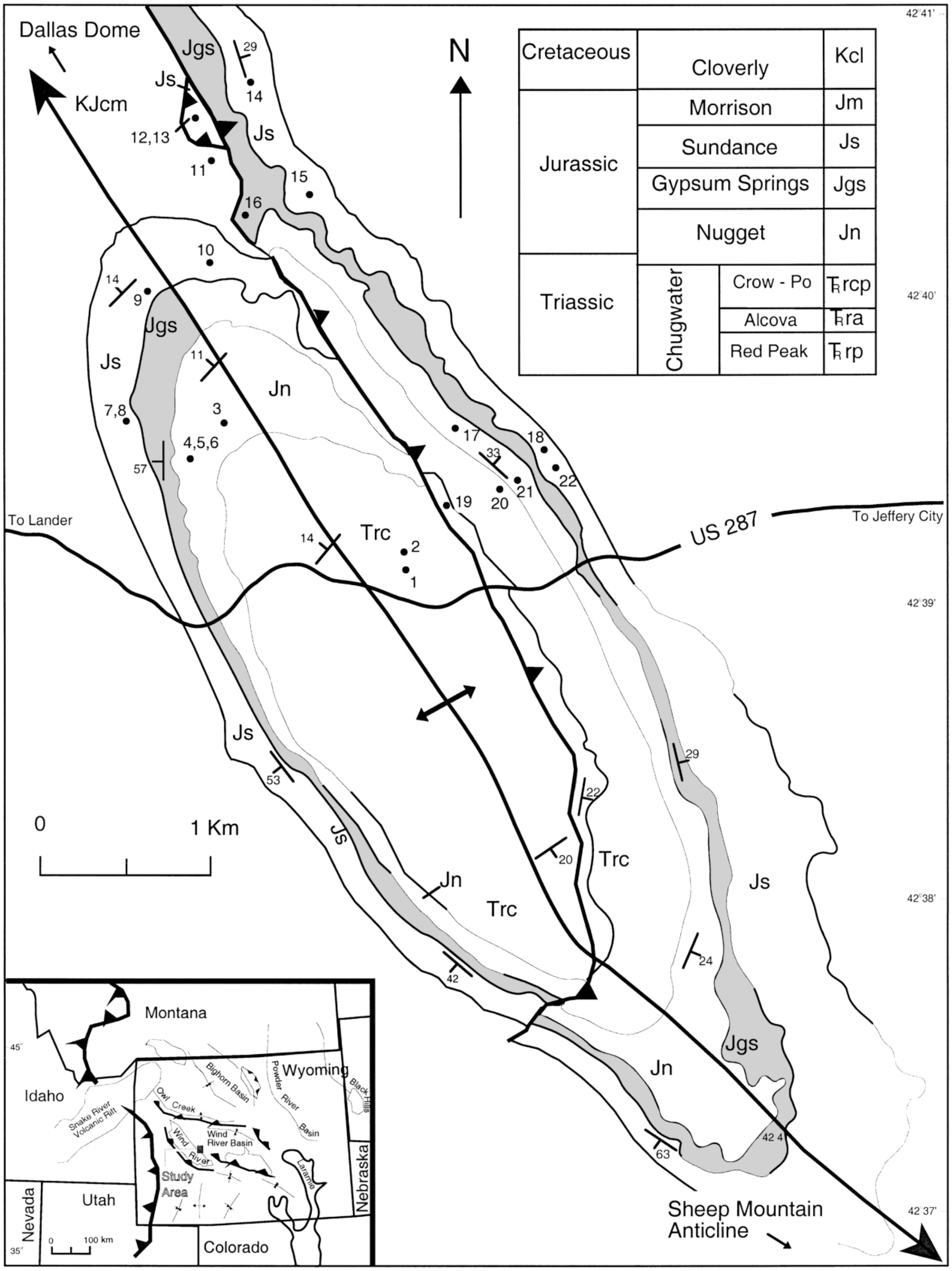

Fig. 1. Local and regional geologic map and stratigraphic column for the Derby Dome area. Triassic Chugwater (Trc) units are not sub-divided on the map. Sample locations are numbered (see Table 1).

Table 1
Details of calcite twin analysis for Derby Dome

	Sample	e_1 (%)	e_1 (tr and pl)	NEVs (%)	Diff. stress (bars)	Rock unit
Veins	2	−1.900	14, 74	27.8	385	Alcova Limestone
	3	−6.450	249, 36	14.3	244	Nugget Sandstone
	6	−4.460	57, 4	13.6	244	Nugget Sandstone
	7a	−3.330	336, 19	16.7	526	Sundance Limestone
	7b	−2.430	135, 41	12.5	667	Sundance Limestone
	8	−3.800	225, 3	28.5	667	Sundance Limestone
	9	−7.400	111, 3	28.6	455	Sundance Limestone
	10	−1.770	146, 5	11.5	670	Sundance Limestone
	13	−2.800	281, 80	9.1	385	Sundance Limestone
	16	−6.020	180, 35	7.1	263	Gypsum Springs LS
	18	−1.100	46, 75.9	0.0	1000	Sundance Limestone
	19	−1.260	117, 17	27.7	2000	Alcova Limestone
	20	−8.210	342, 0.2	5.9	556	CP concretion
	21	−8.835	186, 6	40.0	345	Nugget Sandstone
	22	−3.630	68, 9	25.0	286	Nugget Sandstone
Average		−4.612		16.8	590	
Country Rock	1	−2.690	180, 21	0.0	470	Alcova Limestone
	2	−3.220	17, 0.7	31.8	385	Alcova Limestone
	3	−2.360	5,21	23.5	333	Nugget Sandstone
	4	−1.460	197, 66	21.1	455	Nugget Sandstone
	7	−3.700	163, 14	33.3	625	Sundance Limestone
	8	−2.340	174, 12	6.7	455	Sundance Limestone
	9	−4.330	41, 20	0.0	351	Sundance Limestone
	10	−3.140	113, 25.6	16.7	520	Sundance Limestone
	14	−4.770	167, 42	11.8	333	Sundance Limestone
	15	−1.670	353, 0	5.0	357	Sundance Limestone
	18	−5.590	168, 8	11.8	667	Sundance Limestone
	19	−6.370	171, 5	25.0	588	Alcova Limestone
	22	−3.900	87, 5	20.0	576	Sundance Limestone
Average		−3.339		15.9	470	
Cement	5	−1.490	283, 56	25.0	270	Nugget Sandstone
	11	−2.150	1, 6	0.0	333	Morrison Sandstone
	12	−1.710	357,11.8	18.2	294	Sundance Limestone
	17	−6.304	158, 8	33.3	256	Nugget Sandstone
	21	−3.353	3, 15	6.3	270	Nugget Sandstone
Average		−3.001		16.6	285	

3.3. Derby Dome and the Wind River Basin

With the backdrop of the regional E–W Sevier LPS fabric, the younger sub-horizontal N–S Laramide vein fabric, and the twinning results of Willis and Groshong (1993) along the eastern flank of the Wind River Range, we expected some complexities to the strain history of Derby Dome. We were also aware that this would be the first basement-cored (thick-skinned) fold studied in such detail although Derby Dome is fairly small, and the sedimentary cover on the crystalline corners of other basement uplifts have been studied (e.g. Hennings, 1986a,b; Carson, 1988; Craddock et al., 1988; see also review by Brown, 1993).

Derby Dome (4 × 10 km) is one of five en échelon periclinal, west-verging structures on the northeast flank of the Wind River Range uplift (Ptasynski, 1957) also described by Keefer (1970) (Fig. 1). Domes of this northwest-trending series are cored and locally breeched by an east-dipping thrust fault (a continuation of the Sweetwater Arch thrust to the east) that offsets Archean basement rocks and is synthetic to the Wind River thrust to the west. At the northern end of the folds, the Eocene Wind River Fm. (49 Ma) is offset by this fault and overlain by the Wiggins Fm. (49–45 Ma) of the Absaroka Range bracketing its age of motion, which is complimentary to the fission track and sedimentological uplift ages of Steidtmann et al. (1983) and Cerveny and Steidtmann (1993). Triassic–Cretaceous sediments are exposed around Derby Dome, and the northern half of the fold is accessible without land issues. Thirty-four strain analyses were generated from 22 samples collected from the core (Alcova Limestone) to the highest portion of the eastern limb (Morrison Fm.) on both sides of the thrust that cuts the fold hinge (Fig. 1; Table 1).

3.4. Country rock and cements

Calcite strains in limestone samples (Fig. 2) east and west of Derby Dome preserve a LPS fabric (the bedding planes and compression axis and e_1 shortening axis intersect ±20°) oriented ~E–W (Craddock and van der Pluijm,

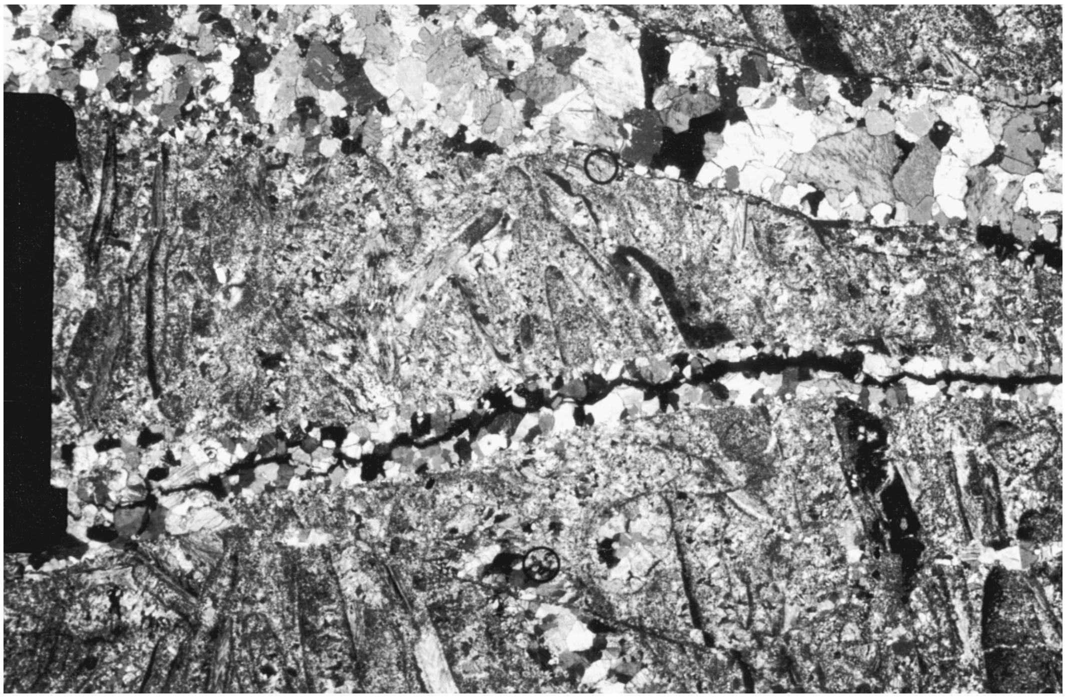

Fig. 2. Photomicrograph of the Sundance Fm. limestone and cross-cutting calcite vein. Scale bar = 2 mm.

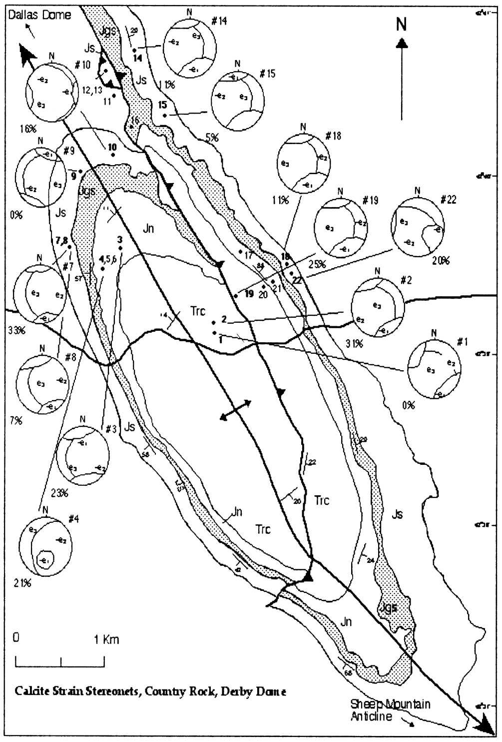

Fig. 3. Lower hemisphere plots of calcite strain gage data for country rock limestones. Great circles are bedding orientations, contoured areas are Turner (1953) compression axes. Axes of the strain ellipsoid are e_1 (maximum shortening [negative]), e_2 (intermediate axis), and e_3 (extension axis [positive]). Negative expected values for each sample are plotted outside each stereonet. See Table 1.

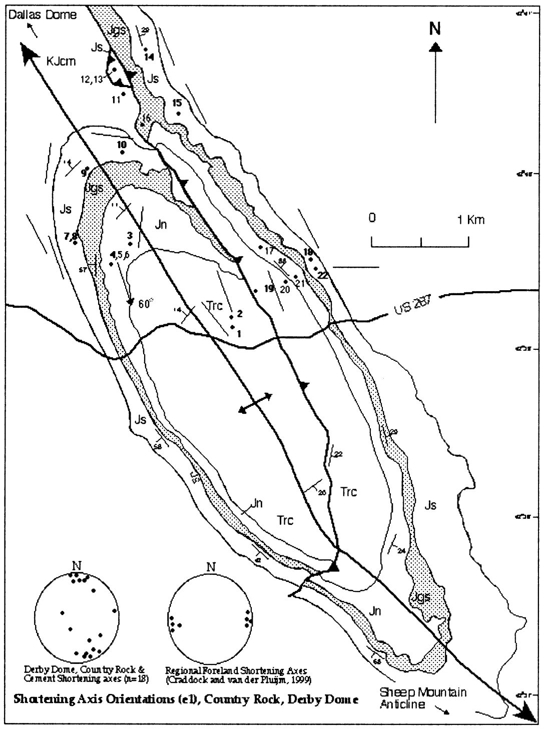

Fig. 4. Map view plot of e_1 shortening strain axes for country rock samples, based on Fig. 3. Steep plunges (sample 4) are indicated by an arrow and the plunge in degrees. Inset stereonets are of the country rock and cement shortening axes (left) and the regional twinning shortening strain pattern in the foreland. See Table 1.

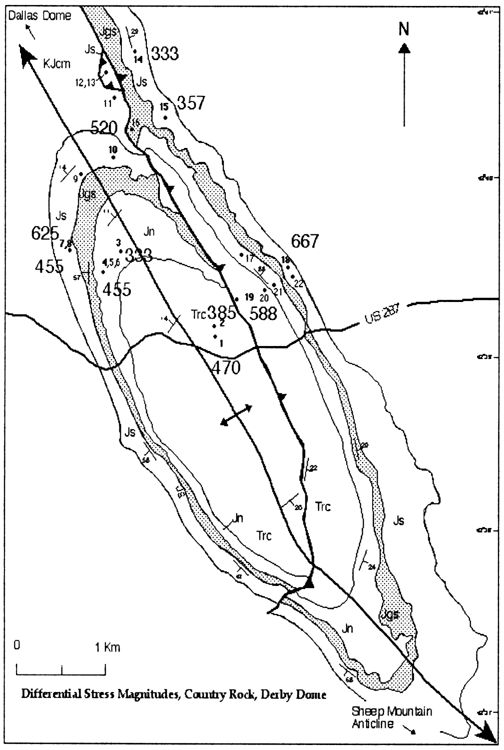

Fig. 5. Differential stress magnitudes (bars; see Table 1) for the country rock suite.

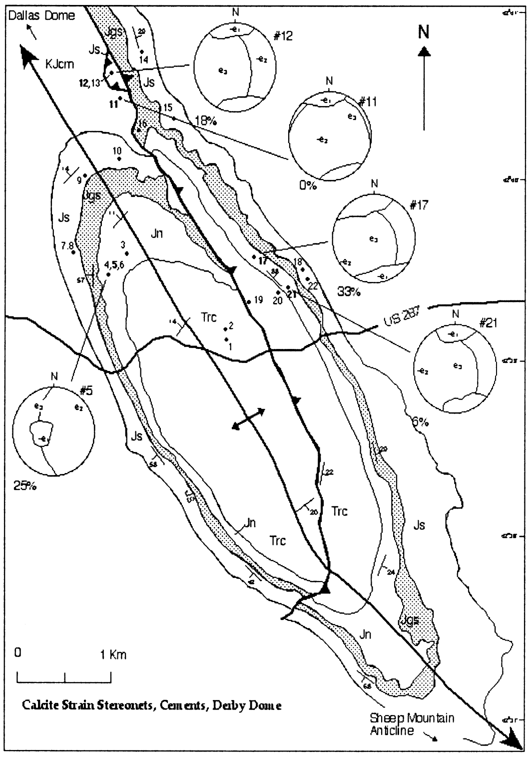

Fig. 6. Lower hemisphere plots of calcite strain gage data for calcite cements. Great circles are bedding orientations, contoured areas are Turner (1953) compression axes. Axes of the strain ellipsoid are e_1 (maximum shortening [negative]), e_2 (intermediate axis), and e_3 (extension axis [positive]). Negative expected values for each sample are plotted outside each stereonet. See Table 1.

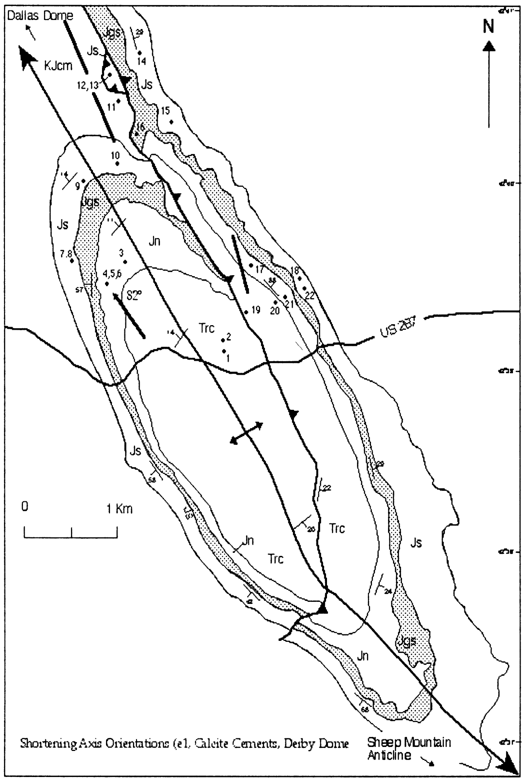

Fig. 7. Map view plot of e_1 shortening strain axes for calcite cement samples, based on Fig. 6.

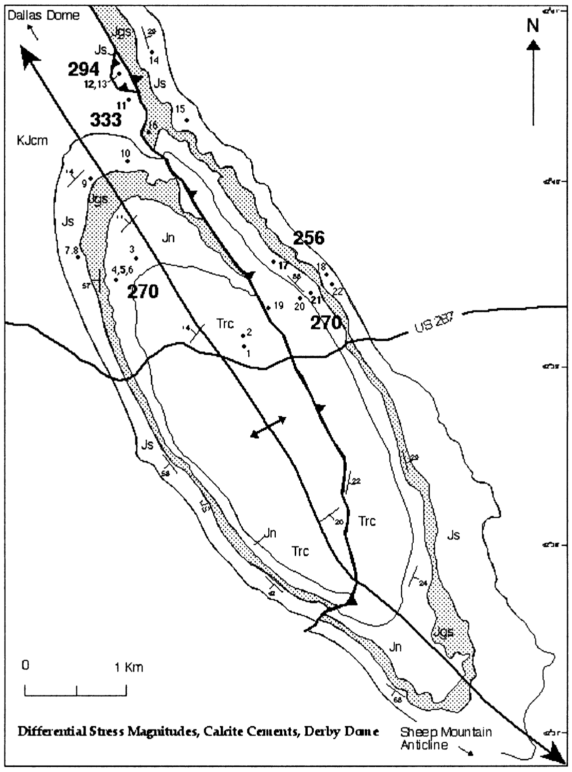

Fig. 8. Differential stress magnitudes (bars; see Table 1) for the calcite cement suite.

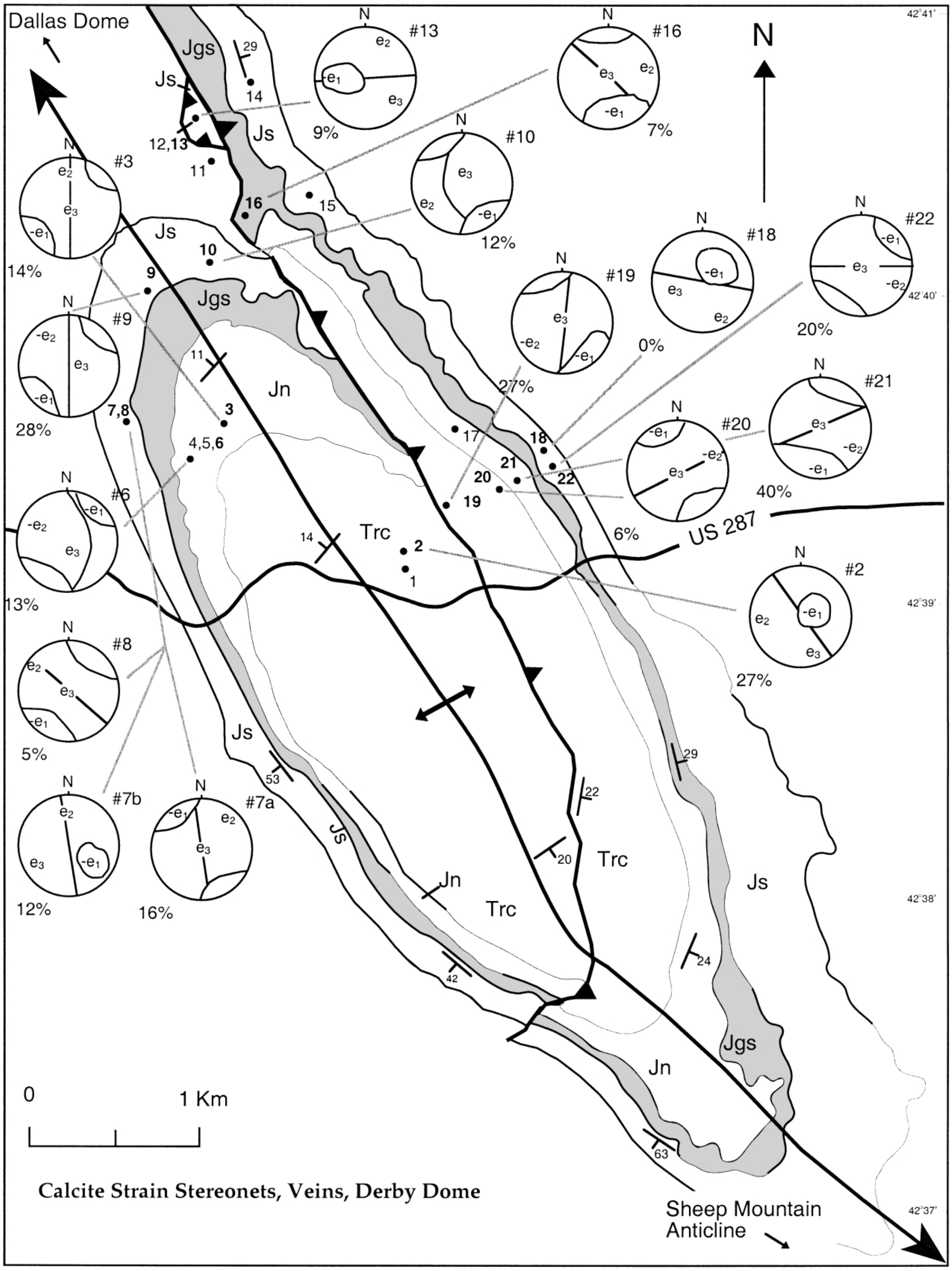

Fig. 9. Lower hemisphere plots of calcite strain gage data for calcite veins. Great circles are vein orientations, contoured areas are Turner (1953) compression axes. Axes of the strain ellipsoid are e_1 (maximum shortening [negative]), e_2 (intermediate axis), and e_3 (extension axis [positive]). Negative expected values for each sample are plotted outside each stereonet. See Table 1. Inset (lower left) stereonets are plots of shortening axes and vein field orientations (poles to planes; $n = 15$). See Section 4.

1999; Table 1, numbers 18, 19, 37–41), which rotates from being hinge-normal to being hinge-parallel as one approaches the fold axis (Figs. 3 and 4). The shortening strain values average −3.3% and the inferred differential stresses (Jamison and Spang, 1976) averages 470 bars (Fig. 5). Country rock and cements strains are identical (Figs. 6–8), and are very different from the cross-cutting veins, so we consider them coeval. In both the country rock, cement and vein data sets, the strain overprint noise (NEVs) increases toward the fold hinge but is not large (avg. = 16%), and in all data sets the twins are thin twins.

3.5. Veins

Sparry synfolding calcite veins (16 strain analyses, −4.6%, 17% NEVs; Figs. 2 and 9–11; Table 1), of varying orientations, preserve two interpretable fabric groups: (1) those that can be interpreted as sub-horizontal, vein-parallel shortening (12 results; where the compression axis contours and e_1 shortening axis intersect the plane of the vein), and (2) non-vein-parallel shortening (the compression axis contours and shortening axis, e_1, do not intersect the plane of the vein). The vein-parallel shortening group contains a mix of sub-horizontal, hinge-parallel shortening strains (samples 7a, 10, 16, 20) and sub-horizontal, hinge-normal shortening strains (samples 2, 3, 6, 9, 13, 21, 22). The non vein-parallel grouping includes four samples (7b, 8, 18, 20), all with different vein orientations where the shortening axis (e_1) is at a high angle to the vein. Inferred differential stress magnitudes (Jamison and Spang, 1976) are also higher for

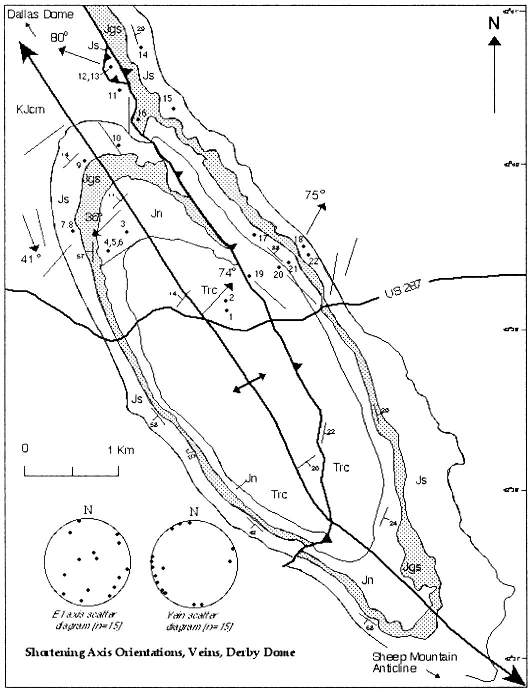

Fig. 10. Map view plot of e_1 shortening strain axes for vein samples, based on Fig. 9. Steep plunges (samples 2, 7b, 13, 18) are indicated by an arrow and the plunge in degrees.

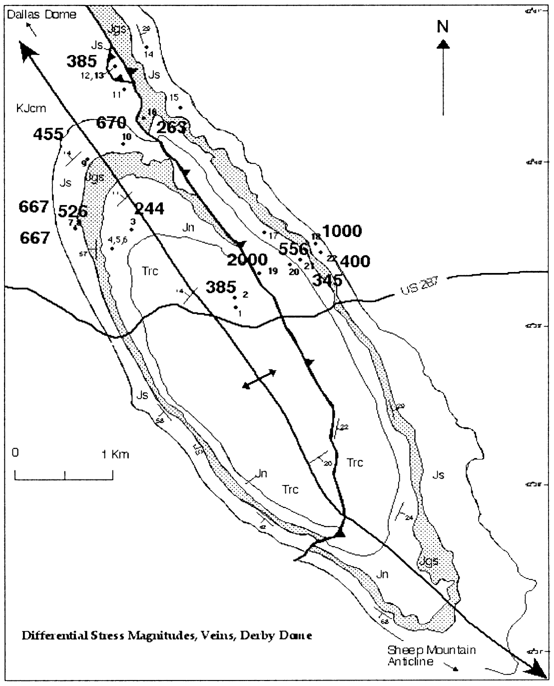

Fig. 11. Differential stress magnitudes (bars; see Table 1) for the vein sample suite.

the vein calcite than for the country rock limestones or cements, but there is not a clear pattern around the fold (avg. = 560 bars, range of 240–2000 bars; Fig. 11).

3.6. Joint and fracture analysis

Dallas Dome is the northern unfaulted equivalent to Derby Dome. The Triassic Red Creek-Nugget section is exposed in the core of the dome making fracture measurement ideal ($n = 74$; Fig. 12). All the fractures are sub-vertical and we find different populations in the same unit on opposite sides of the dome except in the Alcova Limestone. The west limb is dominated by a vertical fracture set that is parallel to the regional transport direction (Mode I; fold axis-normal) although there are other sub-vertical populations. The east limb is dominated by a fold axis-parallel vertical fractures.

4. Discussion

Numerous studies of folding dynamics have utilized the presence of intergranular deformation lamellae in quartz and/or calcite to understand fold genesis, whether within regional (Carter and Friedman, 1965; Friedman and Stearns, 1971; Burger and Hamill, 1976; Schmid et al., 1981; Hennings, 1986a,b; Fisher and Anastasio, 1994) or outcrop-scale structures (Scott et al., 1965; Chapple and Spang, 1974; Spang, 1974; Groshong, 1975; Mitra, 1978; Oertel, 1980; Spang et al., 1980, 1981; Spang and Groshong, 1981; Hudleston and Holst, 1984; Onasch, 1984; Narahara and

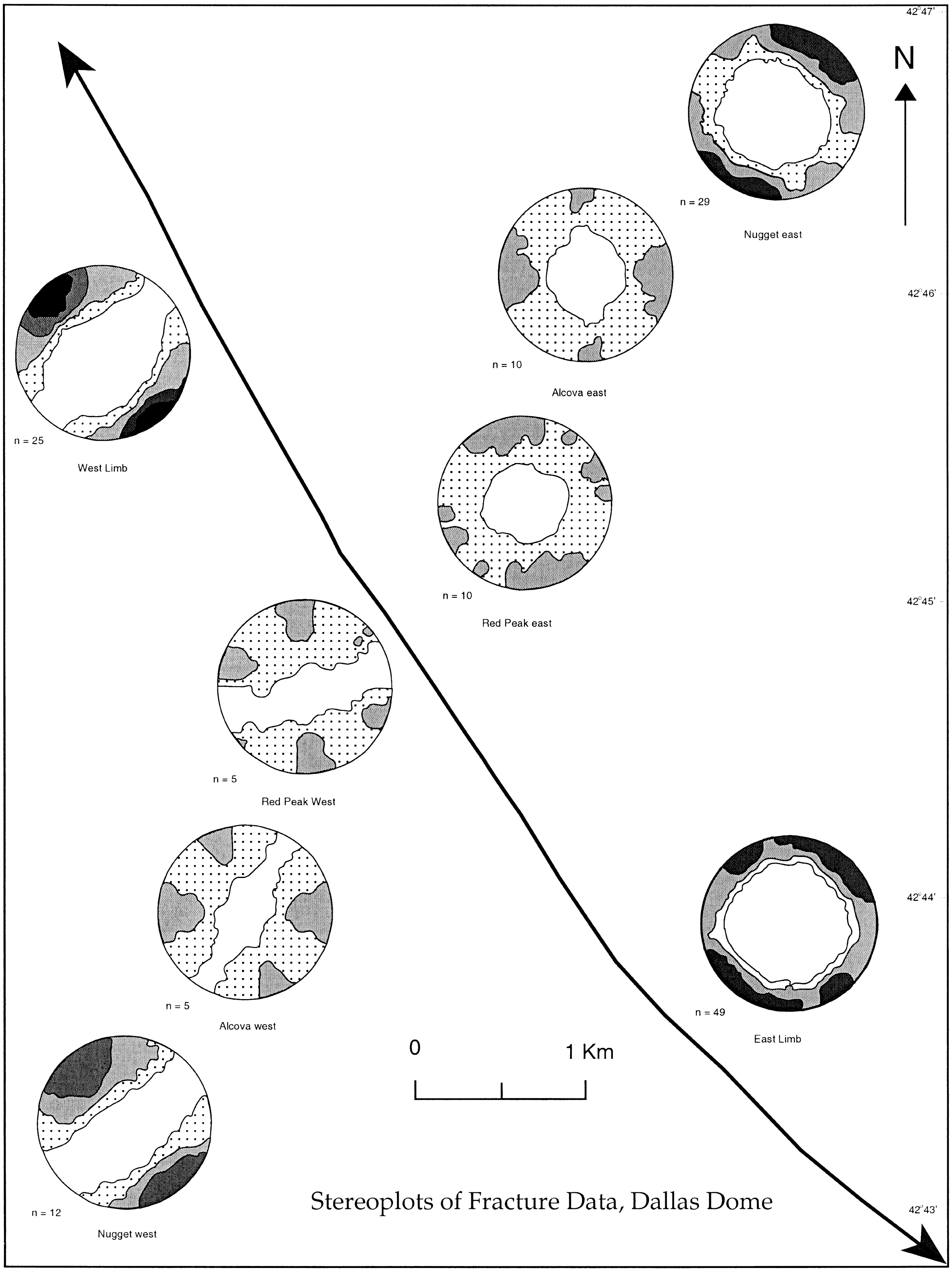

Fig. 12. Lower hemisphere stereonets of rank 1 fracture data (pole to planes) from around Dallas Dome, just north of Derby Dome. Stratigraphic units are the Red Peak, Alcova and Nugget, from bottom to top. Contour intervals are 2, 3 and 5% per 1% area.

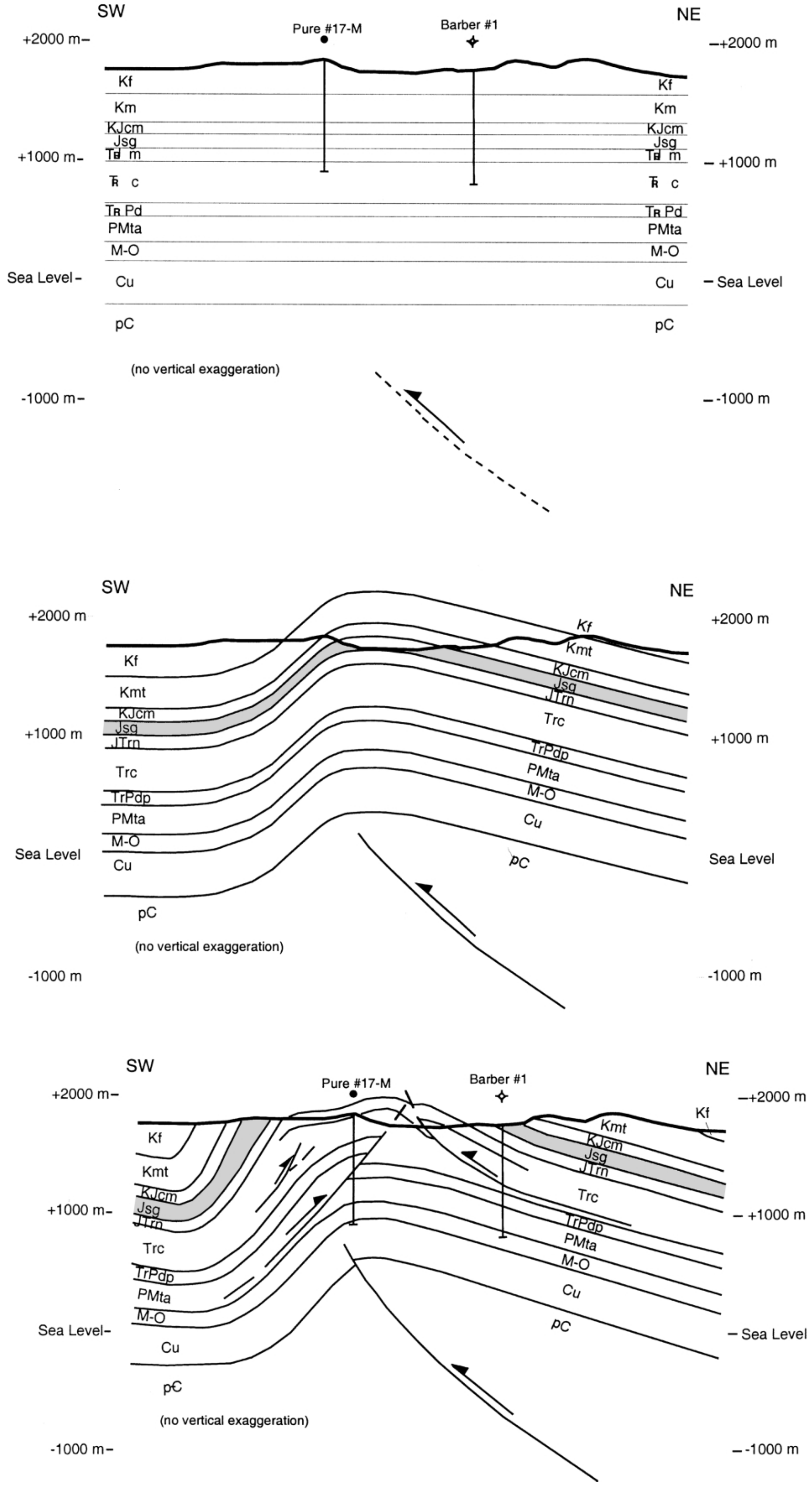

Fig. 13. Map view chronology (A–D) of the geologic development of Derby Dome, tracking the pre-folding e_1 LPS fabric (thin lines) and syn-folding vein (thick lines) fabrics, the fold axis, the NE-dipping Wind River thrust.

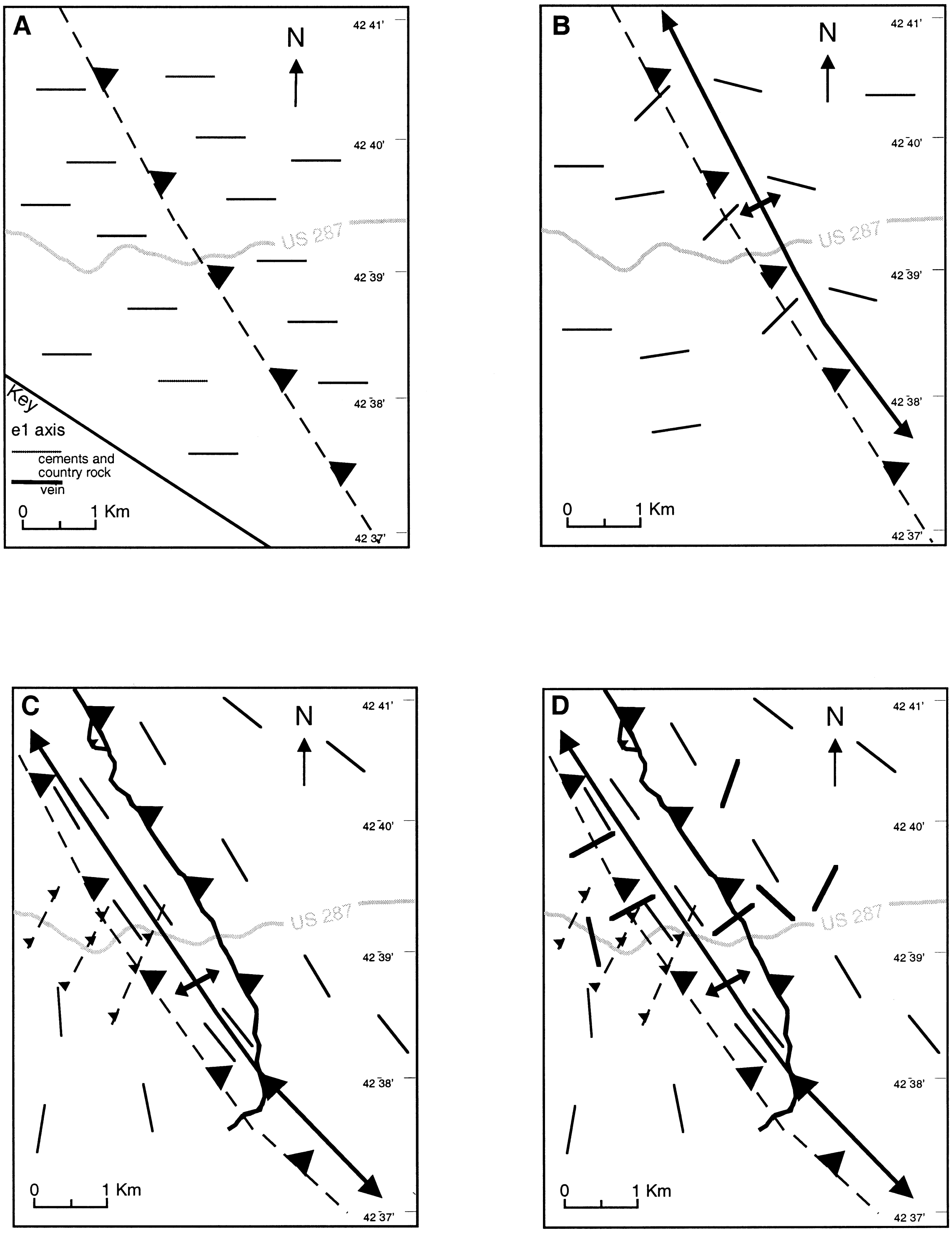

Fig. 14. Cross-sectional chronology (top is oldest, bottom is youngest) of the development of Derby Dome (Fig. 13) based on the subsurface work of Keefer (1970) and Willis and Groshong (1993).

Wiltschko, 1986; Hudleston and Tabor, 1988). The dominant fabric preserved is a pre-folding, layer-parallel shortening strain within the plane of fault transport (plane strain) with little or no syn-folding strain overprint (e.g. Spang and Groshong, 1981). Derby Dome is a thick-skinned Laramide structure formed in the foreland where the pre-folding LPS strain fabric can be used as a passive strain marker during fold development. Orogenic LPS fabrics are known to occur at great distances into the craton of a continent (Craddock and van der Pluijm, 1989; van der

Pluijm et al., 1997) and different orogenic regions preserve unique LPS fabrics across North America (Craddock et al., 1993) or within the individual thrust sheets of an orogenic belt (Craddock, 1992). The twinned calcite in the country rock of Derby Dome preserves this early (Sevier), E–W layer-parallel fabric strain and does not record any twinning strain overprint (low NEVs) as these sediments were folded into the dome structure (Fig. 4, inset). As the LPS fabric was rotated from an E–W orientation into parallelism with the Derby fold axis (N30°W), the synorogenic calcite veins preserve a very complex stress-strain field that is not plane strain and is very chaotic (Fig. 9, inset; see also Hennings et al., 2000).

The pre- and syn-folding stress-strain fields recorded by twinned calcite document rotation of the pre-folding LPS fabric into parallelism with the fold axis with no folding strain overprint despite a complex, non-plane strain deformational history during folding as recorded by the calcite veins (Figs. 13 and 14). Layer-parallel slip, fracturing (Fig. 12), and oblique motions of the NE-dipping Wind River thrust and various minor back-thrusts (Fig. 14) accommodated the folding curvature and asymmetry. Our results are consistent with those of Willis and Groshong (1993) (24 calcite strain analyses from four folds, 13 limestones and 11 calcite cemented sandstones, low NEVs) who found a NE–SW LPS fabric within the cylindrical portions of the folds, and a similar LPS fabric oriented parallel to the fold axes (NW–SE) for the plunging portions of folds. Calcite strain analyses from the adjacent eastern flank (dip-slope) of the Wind River Range preserve two LPS fabrics, one oriented parallel to the range (NW–SE; Willis and Groshong, 1993) and/or one oriented parallel to the regional Sevier fabric (SW–NE; Craddock and van der Pluijm, 1999).

5. Conclusions

The Sevier LPS fabric present in these sediments before Derby Dome was folded has been rotated from an ~E–W orientation into parallelism (NW–SE; ~120° counter-clockwise rotation) with the Derby fold axis. The rotation of this fabric on both sides of the fold axis suggests that oblique motion was important along the various thrusts and back-thrusts (Fig. 14) that truncated the dome. An oblique component (i.e. non-plane strain) of layer-parallel slip must also have been important in the genesis of this fold structure. Syn-folding calcite veins are twinned and record a complex, non-plane strain series of stress-strain field orientations (Fig. 9, inset stereonets) unlike the in-transport stress-strain field of the frontal thin-skinned Pine Mountain thrust (Kilsdonk and Wiltschko, 1988), and not everywhere in accordance with the regional E–W Sevier or younger ~N–S Laramide vein fabric (Craddock, 1992; Craddock and van der Pluijm, 1999).

Acknowledgements

This research was facilitated, in part, by the University of Missouri Branson Field Station, Lander, WY during the summers of 1993–1995, and comprised the basis for Relle's senior research project at Macalester College (1996–1997). The manuscript was greatly improved by Bill Kilsdonk and an anonymous reviewer.

References

Allmendinger, R.W., 1982. Analysis of microstructures in the Meade plate of the Idaho–Wyoming foreland thrust belt, USA. Tectonophysics 85, 221–251.

Apotria, T.G., 1990. The kinematics and mechanics of oblique ramp deformation within fold-and-thrust belts. Ph.D. dissertation, Texas A&M University, College Station, TX, 235pp.

Apotria, T.G., 1995. Thrust sheet rotation and out-of-plane strains associated with oblique ramps: an example from the Wyoming salient, USA. Journal of Structural Geology 17, 647–662.

Armstrong, F.C., Oriel, S.S., 1965. Tectonic development of the Idaho–Wyoming thrust belt. American Association of Petroleum Geologists Bulletin 49, 1847–1866.

Berg, R.R., 1962. Mountain flank thrusting in Rocky Mountain foreland, Wyoming and Colorado. Bulletin of the American Association of Petroleum Geologists 46, 2019–2032.

Bird, P., 1988. Formation of the Rocky Mtns., western United States: a continuum computer model. Science 239, 1501–1507.

Brown, W.G., 1993. Structural style of Laramide basement-cored uplifts and associated folds. In: Snoke, A.W., Steidtmann, J.R., Roberts, S.M. (Eds.), Geology of Wyoming, Geological Survey of Wyoming Memoir 5, pp. 312–371.

Budai, J.M., Wiltschko, D.V., 1987. Structural controls on syntectonic diagenesis within the Haystack Peak region of the Absaroka thrust sheet, Idaho–Wyoming–Utah thrust belt. 38th W.G.A. Field Conference Guidebook, pp. 55–68.

Burger, R., Hamill, M.N., 1976. Petrofabric stress analysis of the Dry Creek Ridge anticline, Montana. Geological Society of America Bulletin 87, 555–566.

Burkhard, M., 1993. Calcite twins, their geometry, appearance and significance as stress-strain markers and indicators of tectonic regime: a review. Journal of Structural Geology 15, 351–368.

Carson, D.W., 1988. A regional analysis of calcite twinning strain in the Bighorn Mountains, N. Wyoming. M.S. thesis, Iowa State University, 71pp.

Carter, N.L., Friedman, M., 1965. Dynamic analysis of deformed quartz and calcite from the Dry Creek Ridge anticline, Montana. American Journal of Science 262, 747–785.

Cerveny, P.F., Steidtmann, J.R., 1993. Fission track thermochronology of the Wind River Range, Wyoming; evidence for the timing and magnitude of Laramide exhumation. Tectonics 12 (1), 77–91.

Chapple, W.M., Spang, J.H., 1974. Significance of layer parallel slip during folding of layered sedimentary rocks. Geological Society of America 85, 1523–1534.

Craddock, J.P., 1992. Transpression during tectonic evolution of the Idaho–Wyoming fold-and-thrust belt. Geological Society of America Memoir 179, 125–139.

Craddock, J.P., Pearson, A., 1994. Non-coaxial horizontal shortening strains preserved in amygdule calcite, DSDP Hole 433C, Suiko Seamount. Journal of Structural Geology 16, 719–724.

Craddock, J.P., van der Pluijm, B.A., 1988. Kinematic analysis of an en echelon-continuous vein complex. Journal of Structural Geology 10, 445–452.

Craddock, J.P., van der Pluijm, B.A., 1989. Late Paleozoic deformation of the cratonic carbonate cover of eastern North America. Geology 17, 416–419.

Craddock, J.P., van der Pluijm, B.A., 1999. Regional stress-strain fields of Sevier–Laramide tectonism from calcite twinning data, west-central North America. Tectonophysics Special Volume 305, 275–286.

Craddock, J.P., Kopania, A., Wiltschko, D.V., 1988. Interaction between the northern Idaho–Wyoming thrust belt and bounding basement blocks, central western Wyoming. Geological Society of America Memoir 171, 333–351.

Craddock, J.P., Moshoian, A., Pearson, A.M., 1991. Kinematic analysis from twinned calcite strains in the marble mylonites of the central Grenville province, Canada. Geological Society of America, Abstracts with Programs 15, 236.

Craddock, J.P., Jackson, M., van der Pluijm, B.A., Versical, R., 1993. Regional shortening fabrics in eastern North America: far-field stress transmission from the Appalachian–Ouachita orogenic belt. Tectonics 12, 257–264.

Craddock, J.P., Pearson, A., McGovern, M., Moshoian, A., Donnelly, K., 1997. Post-extension shortening strains preserved in calcites of the Keweenawan rift. Geological Society of America Memoir 312, 115–126.

Dorr, J.A., Jr., Spearing, D.R., Steidtmann, J.R., 1977. In: OTHER-REF. Deformation and deposition between a foreland uplift and an impinging thrust belt, Hoback basin, Wyoming. Geological Society of America Special Paper 177, 82pp.

Engelder, T., 1979. The nature of deformation within the outer limits of the central Appalachian foreland fold-and-thrust belt in New York state. Tectonophysics 55, 289–310.

Engelder, T., 1993. Stress Regimes in the Lithosphere, Princeton University Press, 457pp.

Ferrill, D.A., 1991. Calcite twin widths and intensities as metamorphic indicators in natural low-temperature deformation of limestone. Journal of Structural Geology 13, 675–677.

Ferrill, D.A., 1998. Critical re-evaluation of differential stress estimates from calcite twins in coarse-grained limestone. Tectonophysics 285, 77–86.

Fisher, D.M., Anastasio, D.J., 1994. Kinematic analysis of a large scale leading edge fold, Lost River Range, Idaho. Journal of Structural Geology 16 (3), 337–354.

Friedman, M., Stearns, D.W., 1971. Relations between stresses inferred from calcite twin lamelae and macrofractures, Teton Anticline, Montana. Geological Society of America Bulletin 82, 3151–3162.

Gries, R., 1983. Oil and gas prospecting beneath Precambrian of foreland thrust plates in Rocky Mtns. Bulletin of the American Association of Petroleum Geologists 67, 1–28.

Groshong, R.H. Jr, 1972. Strain calculated from twinning in calcite. Bulletin of the Geologists Society of America 83, 2025–2038.

Groshong, R.H. Jr, 1974. Experimental test of least-squares strain calculations using twinned calcite. Bulletin of the Geologists Society of America 85, 1855–1864.

Groshong, R.H. Jr, 1975. Strain, fractures, and pressure solution in natural single-layer folds. Bulletin of the Geologists Society of America 86, 1363–1376.

Groshong, R.H. Jr, Teufel, L.W., Gasteiger, C.M., 1984. Precision and accuracy of the calcite strain-gage technique. Bulletin of the Geologists Society of America 95, 357–363.

Hennings, P., 1986a. Petrofabric implications for cover rock adjustment in basement-cored anticline: Dry Fork Ridge, Bighorn Mtns., Wyoming. Geological Society of America, Abstracts with Programs 18 (6), 635.

Hennings, P., 1986. Basement-cover relations of the Dry Fork Ridge anticline termination, northeastern Bighorn Mountains, Wyoming and Montana. M.S. thesis, Texas A&M University, College Station, Texas, 187pp.

Hennings, P.H., Olson, J.E., Thompson, L.B., 2000. Combining outcrop data and 3-D structural models to characterize fractured reservoirs: an example from Wyoming. American Association of Petroleum Geologists Bulletin 84, 830–849.

Hudleston, P.J., Holst, T.B., 1984. Strain analysis and fold shape in a limestone layer and implications for layer rheology. Tectonophysics 106, 321–347.

Hudleston, P.J., Tabor, J.R., 1988. Strain and fabric development in a buckled clacite vein and rheological implications. Bulletin of the Geological Institutions of the University of Uppsala 14, 79–94.

Jamison, W.R., Spang, J.H., 1976. Use of calcite twin lamellae to infer differential stress. Geological Society of America Bulletin 87, 868–872.

Jordan, T.E., 1981. Thrust loads and foreland basin evolution, Cretaceous, western United States. Bulletin of the American Association of Petroleum Geologists 65, 2506–2520.

Keefer, W.R., 1970. Structural Geology of the Wind River Basin, Wyoming in Geology of the Wind River Basin, Central Wyoming, U.S. Geological Survey Report, pp. D1–D35.

Kilsdonk, W., Wiltschko, D.V., 1988. Deformation mechanisms in the southeastern ramp region of the Pine Mountain block, Tennessee. Geological Society of America Bulletin 100, 644–653.

Kraig, D.H., Wiltschko, D.V., 1987. Effects on the calcite fabric (Madison Fm.) of the impingement of the Darby/Hogsback thrust sheet and LaBarge Platform, Snider Basin area. Wyoming Geological Association 38th Guidebook.

Lacombe, O., Laurent, P., 1996. Determination of deviatoric stress tensors based on inversion of calcite twin data from experimentally deformed monophase samples: preliminary results. Tectonophysics 255, 189–202.

Marshak, S., Paulsen, T., 1996. Midcontinent U.S. fault and fold zones: a legacy of Proterozoic intracontinental extensional tectonism? Geology 24, 151–154.

Marshak, S., Karlstrom, K., Timmons, J.M., 2000. Inversion of Proterozoic extensional faults: an explanation for the pattern of Laramide and Ancestral Rockies intracratonic deformation, United States. Geology 28, 735–738.

Mitra, G., 1978. Microscopic deformation mechanisms and flow laws in quartites within South Mountain anticline. Journal of Geology 86, 129–152.

Narahara, D.K., Wiltschko, D.V., 1986. Deformation in the hinge region of a chevron fold, Valley and Ridge Province, central Pennsylvania. Journal of Structural Geology 8, 157–168.

Oertel, G., 1980. Strain in ductile rocks on the convex side of a folded competent bed. Tectonophysics 66, 15–34.

Oldow, J.S., Bally, A.W., Ave Lallement, H.G., Leeman, W.P., 1989. Phanerozoic evolution of the North American Cordillera; United States and Canada. In: Bally, A.W., Palmer, A.R. (Eds.), The Geology of North America—an Overview. Boulder, CO, GSA DNAG, vol. A, pp. 139–232.

Onasch, C.M., 1984. Petrofabric test of viscous folding theory. Tectonophysics 106, 141–153.

van der Pluijm, B.A., Craddock, J.P., Graham, B.R., Harris, J.H., 1997. Paleostress in cratonic North America: implications for deformation of continental interiors. Science 277, 792–796.

Ptasynski, H., 1957. Dallas–Derby dome area. Wyoming Geologists Association 12th Annual Field Conference Guidebook, pp. 127–131.

Rowe, K.J., Rutter, E.H., 1990. Paleostress estimation using calcite twinning: experimental calibration and application to nature. Journal of Structural Geology 12, 1–17.

Schmid, S.M., Casey, M., Starkey, J., 1981. The microfabric of calcite tectonites from the Helvetic Nappes (Swiss Alps). In: Thrust and Nappe Tectonics. The Geological Society of London, pp. 151–158.

Scott, W.H., Hansen, E., Twiss, R.J., 1965. Stress analysis of quartz deformation lamellae in a minor fold. American Journal of Science 263, 729–746.

Smithson, S.B., Brewerm, J., Kaufman, S., Oliver, J., Hurich, C., 1978. Question of the Wind Thrust, Wyoming, resolved by COCORP deep reflection data and by gravity data. Wyoming Geological Association Guidebook, Thirtieth Annual Field Conference, pp. 227–233.

Spang, J.H., 1974. Numerical dynamic analysis of calcite twin lamellae in the Greenport Center syncline. American Journal of Science 274, 1044–1058.

Spang, J.H., Groshong, R.H. Jr, 1981. Deformation mechanisms and strain history of a minor fold from the Appalachian Valley and Ridge Province. Tectonophysics 72, 323–342.

Spang, J.H., Simony, P.S., Mitchell, W.J., 1980. Strain and folding mechanism in a similar style fold from the northern selkirks of the Canadian Cordillera. Tectonophysics 66, 253–267.

Spang, J.H., Wolcott, T.L., Serra, S., 1981. Strain in the ramp regions of two minor thrusts, southern Canadian Rocky Mountains, American Geophysical Monograph 24, pp. 243–250.

Steidtmann, J.R., McGee, L.C., Middleton, L.T., 1983. Laramide sedimentation, folding, and faulting in the southern Wind River Range, Wyoming. Rocky Mountain Association of Geologists, pp. 161–167.

Suppe, J., 1983. Geometry and kinematics of fault bend folding. American Journal of Science 283, 684–721.

Teufel, L.W., 1980. Strain analysis of experimental superposed deformation using calcite twin lamellae. Tectonophysics 65, 291–309.

Turner, F.J., 1953. Nature and dynamic interpretation of deformation lamellae in calcite of three marbles. American Journal of Science 251, 276–298.

Varga, R.J., 1993. Rocky Mtn. foreland uplifts: products of a rotating stress field or strain partitioning? Geology 21, 1115–1118.

Willis, J.J., Groshong, R.H., Jr, 1993. Deformational style of the Wind River uplift and associated flank structures, Wyoming. Wyoming Geological Association Symposium Guidebook, pp. 337–375.

Wiltschko, D.V., Dorr, J.A., 1983. Timing of deformation in the overthrust belt of Idaho, Wyoming and Utah. Bulletin of the American Association of Petroleum Geologists 67, 1304–1322.

Wiltschko, D.V., Medwedeff, D.A., Millson, H.E., 1985. Distribution and mechanisms of strain within rocks on the northwest ramp of Pine Mountain block, southern Appalachian foreland: a field test of theory. Geological Society of America Bulletin 96, 426–435.