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CALCITE TWINNING STRAIN ANALYSIS OF THE ALLOCHTHONOUS JURASSIC SUNDANCE, SOUTH FORK DETACHMENT, NORTHWEST WYOMING

MAREN MATHISEN, Augustana College
Research Advisor: Jeffrey Strasser and Michael Wolf

INTRODUCTION

The South Fork detachment (SFD) is a 10 by 40 km rootless, folded structure exposed along the South Fork of the Shoshone River. It consists of at least 1,250 m of Jurassic Sundance through Cretaceous Cody strata that has been displaced up to 10 km, likely from the northwest (Beutner and Hauge, 2009). The upper plate structures are oriented ~SW-NE and the shortening direction is interpreted to be ~NW-SE. The youngest exposures are part of the Eocene Absaroka volcanic field and the oldest are part of the Jurassic Gypsum Springs Formation (Clarey, 1990). Repetition above the Jurassic Gypsum Springs (directly below the Jurassic Sundance) is seen in wells drilled through the South Fork allochthon, but only minimal deformation occurs below (Clarey, 1990). The decollement begins along the Jurassic Gypsum Springs and/or Sundance Formations and to the southeast ramps upward to a décollement along the Upper Cretaceous Cody Shale and then the Tertiary Willwood Formation (Beutner and Hauge, 2009). Fold and thrust geometries suggest up to 10 km of shortening (Beutner and Hauge, 2009).

The SFD has been interpreted to be the front of a gravity slide, older than and unrelated to the Heart Mountain detachment (Blackstone, 1985; Pierce, 1957, 1986), the easternmost expression of the Cordilleran overthrust belt (Clarey, 1990), or the toe of the Heart Mountain detachment (Beutner and Hauge, 2009; Clarey, 2008, 2009). The goal of this study was to further clarify the circumstances and mechanisms related to emplacement of the South Fork allochthon and possibly advance one of the previously proposed interpretations.

GEOLOGIC SETTING AND BACKGROUND

The geology in northwestern Wyoming became increasingly complex with the overlap of the Sevier and Laramide orogenies during the Cretaceous to Eocene and the Early Eocene onset of Absaroka volcanism. The resulting geologic features include anticlinal structures, detachment features, volcanic debris flows, and landslides. Large Precambrian-cored foreland anticlinal structures include Rattlesnake-Cedar Mountain, Pat O'Hara Mountain and the southeastern edge of the Beartooth Mountains; detachment features include the Heart Mountain detachment, South Fork detachment, and Reef Creek detachment; Absaroka volcanic activity has produced a thick sequence of igneous and volcaniclastic rocks; and more recent Quaternary landslides have also occurred on a large scale (Blackstone, 1985).

The SFD likely has a connection to the contemporaneous Eocene events proximally located in NW Wyoming. Cross-cutting field relationships allow constraints on the timing of emplacement of the South Fork allochthon. [The allochthon offsets the Eocene Willwood Formation (~53 Ma), but is also overlain by younger Willwood and the Wapiti Deer Creek debris flow (ca. 48.9 Ma).] The majority of Absaroka volcanism occurred between 55 and 45 Ma (Feeley and Cosca, 2003) and the Heart Mountain detachment occurred at 48.9 Ma (Craddock et al., 2009), both while the thin-skinned Sevier and thick-skinned Laramide orogenies were in their final stages. Though interrelations of these events have been proposed, sufficient field evidence has not been found to confidently link them.

The two major detachment systems, the Heart Mountain detachment (HMD), composed of Paleozoic carbonates, and the SFD, of Mesozoic strata, appear to have either a direct or indirect connection. The Heart Mountain allochthon is more than an order of magnitude larger in volume than any other subaerial landslide or debris avalanche ever documented, with an extent of greater than 3400km^2, and has been investigated intensely for more than a century (Beutner and Hauge, 2009). The SFD, with an aerial extent of greater than 1400 km^2, has been studied since Dake first recognized and named it in 1918 (Blackstone, 1985). The SFD has received much less scientific attention than the HMD and a number of perplexing problems still remain.

Heart Mountain Detachment

The HMD consists of Ordovician through Mississippian carbonate rocks and overlying Eocene rocks, two to four kilometers in thickness and greater than 1,100 km2 in area, that were transported as far as 50 km and over an area of 3,400 km^2 (Beutner and Hauge, 2009; Malone and Craddock, 2008). The transport was in a southeastern direction, from the northeast flank of the northern Absarokas to the western edge of the Big Horn Basin (Craddock et al., 2009). Hypotheses for emplacement are abundant and include rapid tectonic denudation, rapid continuous allochthon without tectonic denudation, slow moving continuous allochthon, and volcanic collapse (Craddock et al., 2009). Research by Feeley and Cosca (2003), Smith et al. (2003), and Rhodes et al. (2007), narrows the possible timeframe for emplacement to between 49.7 and 49.5 Ma, leading to an increased support of catastrophic emplacement (Craddock et al., 2009).

South Fork Detachment

The emplacement of the allochthonous SFD has been attributed to several different mechanisms. Blackstone (1985) suggests that movement is considered to be free-sliding due to the force of gravity and that tectonic denudation occurred upslope from the present surface trace of the decollement. He also states that the Heart Mountain remnants rest stratigraphically above the North Fork plate, which overlies the

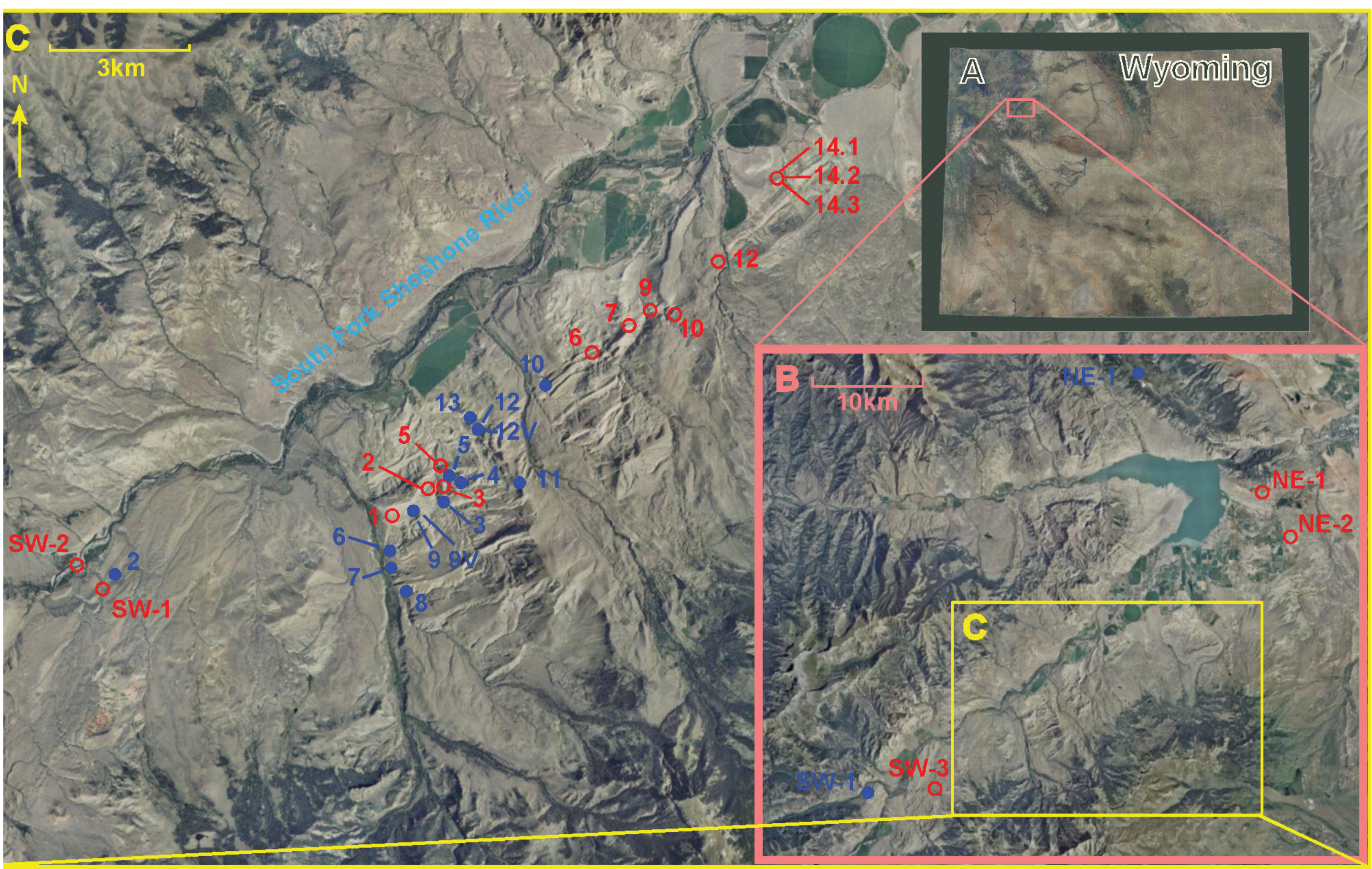

Figure 1. Map of the study area and sample locations. Red ◦= 2010 sample, Blue • =2011 sample. A) Wyoming map showing study area, B) Extent of field area ,including SW and NE lower plate sample locations, and C) the SFD, the area of focus.

South Fork Plate, indicating that the SFD is older than the HMD.

Beutner and Hauge (2009) concluded that the South Fork and Heart Mountain detachment systems may be linked in the subsurface, allowing the possibility that they are both due to the multistage Eocene collapse of an active Absaroka volcanic pile. They suggest that an early-phase collapse caused non-catastrophic spreading, with extension above the proximal part of the HMD, linked to distal contraction above the SFD, and that a late-phase collapse caused a final catastrophic event, with extensional deformation in proximal and distal areas of the HMD (Beutner and Hauge, 2009).

Clarey (1990) presents an alternate theory: that all of the observed structural geometries can be attributed to development under a compressional regime as in the Wyoming-Utah-Idaho thrust belt. He concluded that the South Fork fault is a fault system representing a single deformational episode due to a compressional regime during the early to middle Eocene (Clarey, 1990). Clarey (2008, 2009) now advocates a single continuous catastrophic emplacement of the allochthon due to gravity and “pushing” from the HMD.

Calcite twinning strain analyses conducted by Katherine Kravitz (2011) show that strain and stress in the upper and lower plates of the SFD resulted due to emplacement of the allochthon during a detachment event. The shortening axes within in the upper plate show overall NW-SE orientations, which corresponds to the accepted direction of southeast allochthonous transport, and the scatter among data likely result from rotation and tilting of beds as the allochthon moved (Kravitz, 2011). She concluded that although there is scatter in the data, there is not enough to suggest an additional deformational event, which was unexpected since the nearby HMD contains Sevier-Laramide related strain (Kravitz, 2011).

METHODS

Field Methods

Sixteen oriented samples for calcite twinning strain analysis were collected from within the Sundance Formation in the SFD upper plate (Fig. 1). Our research group re-mapped the upper plate of the South Fork detachment at a scale of 1:24,000 in the Belknap Creek 7.5 Minute Quadrangle in order to provide context for our research, calcite twinning sampling, and interpretation. Previous mapping by Pierce and Nelson (1969) lacked sufficient structural measurements, the inclusion of important structures, and has been repeatedly questioned by scientists conducting research in the area.

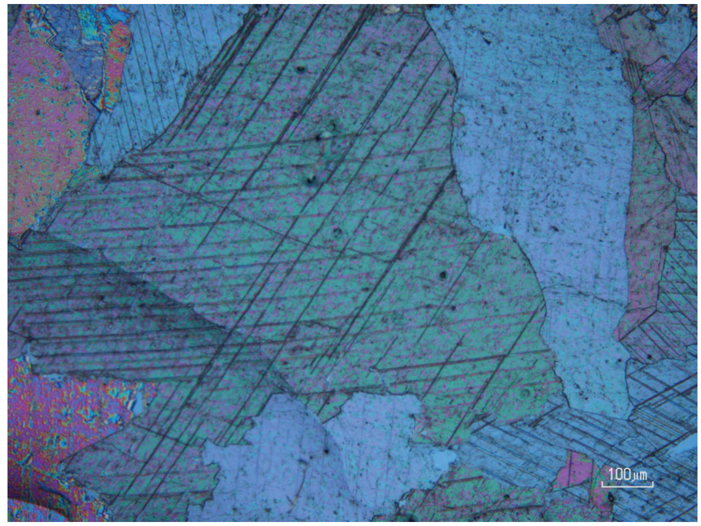

Figure 2. Photomicrograph of twin sets in deformed calcite (SFD-11-12V).

Calcite Twinning

Calcite twinning can be used as a measure of finite strain and differential stress because the twinning takes place along certain crystallographic planes, over a specific angle, and strain-hardens once twinned (van der Pluijm and Marshak, 2004). The initial shape is known from the crystallography of calcite. The deformed shape (see Fig. 2) is measured, as long as the calcite is coarse enough for optical determination of the crystallographic axes, with a microscope that has a four-axis universal-stage (Groshong, 1972). Sixteen samples from the Jurassic Sundance Formation, including 2 calcite veins, were measured in thin section. They were analyzed in conjunction with 16 samples also collected from within the Sundance Fm. as part of a 2010-2011 Keck project. Strain ellipsoid axis orientations were computed using the calcite least-squares strain-gage technique (Groshong, 1972, 1974).

Limestone samples and calcite veins were analyzed separately. The least-squares strain-gage technique yields positive expected shear strain values (PEV) and negative expected shear strain values (NEV) for each twin set measured in an aggregate of grains in a thin section. The presence of NEVs can signify a single inhomogeneous strain, a coaxial superposed deformation, or when greater than 40% of grains in a thin section are NEVs, a second non-coaxial twinning deformation (Teufel, 1980). When plotted on a stereonet, twinning strains are interpreted to preserve layer-parallel shortening strains (LPS) if the shortening axis (e1) and the contoured maxima of the compression axes intersect the bedding orientation of the sample, and layer-normal shortening if they do not.

RESULTS

Lower Plate Strain

Eight lower plate samples to the southwest and northeast were analyzed (Table 1). Almost all lower plate samples preserve layer-parallel shortening (LPS). The only exception is NE-10-1, which preserves layer-normal shortening (LNS). The lower plate samples to the southwest all contain a minimal amount of NEVs (avg. 6%), which indicates only one twinning event. Shortening axes in all four SW samples proximal to the SFD are oriented to the N-NW. The shortening axis of SW-11-1 trends NE. NE samples from Rattlesnake Mountain average 18%. This is higher than in the southwest lower plate, but is still not significant enough to indicate a separate non-coaxial twinning event.

Upper Plate Strain

The majority of the 23 upper plate twinning samples preserve a LPS fabric (Table 1). NEVs are relatively low (12.2%) and the orientation of shortening axes is highly variable, indicating a second deformational event with reorientation of the strain axes, but no secondary twinning. Samples from the western Rock Creek and Belknap Ranch areas of the SFD, when compared to the samples farther east, near Carter Mountain Road and Castle Rock Angus Ranch, do not appear to have any distinct differences.

Calcite Twinning Strains

Sample	Bedding Orientation	Location	*n* =	NEV (%)	Strain Orientation (T, P) e_1	e_2	e_3	Fabric Interpretation
SW-10-1	N30°E, 40°NW	LP	57	8.8	333°, 87°	181°, 11°	087°, 16°	LPS
SW-10-2	N35°E, 28°NW	LP	40	2.3	230°, 77°	358°, 13°	094°, 18°	LPS
SW-10-3	N30°E, 12°NW	LP	53	7.5	311°, 31°	216°, 18°	098°, 55°	LPS
SW-11-1	N40°W, 25°SW	LP	21	9.5	049°, 03°	235°, 86°	139°, 01°	LPS
SW-11-2	N10°E, 40°NW	LP	35	25.7	278°, 19°	124°, 69°	010°, 09°	LPS
NE-10-1	N70°E, 32°S	LP	35	24.5	235°, 14°	241°, 16°	101°, 59°	LNS
NE-10-2	NS, 28°W	LP	37	23.5	310°, 18°	043°, 06°	149°, 70°	LPS
NE-11-1	N30°E, 25°NW	LP	30	6.6	217°, 01°	307°, 01°	120°, 89°	LPS
SFD-10-1	EW, 88°N	UP	36	28.3	091°, 10°	189°, 42°	351°, 46°	LPS
SFD-10-2	Vertical	UP	39	24.0	266°, 21°	153°, 45°	012°, 39°	LPS
SFD-10-3	N40°E, 18°S	UP	37	19.1	162°, 35°	268°, 21°	021° 48°	LPS
SFD-10-5.1	Vertical	UP	29	37.5	019°, 00°	280°, 48°	110°, 44°	LPS
SFD-10-6	N53°E, 50°SE	UP	50	8.0	043°, 09°	296°, 64°	143°, 24°	LPS
SFD-10-7	N45°E, 45°S	UP	48	20.8	245°38°	041°, 50°	054°, 12°	LPS
SFD-10-10	N40°E, 55°SE	UP	35	20.0	206°, 05°	110°, 48°	300°, 42°	LPS
SFD-10-12	N30°E, 55°SE	UP	50	0.0	122°, 61°	013°, 12°	279°, 28°	LPS
SFD-10-14.1	N50°E, 55°N	UP	49	2.0	285°, 35°	032°, 24°	148°, 44°	LPS
SFD-10-14.2	N45°E, 45°S	UP	50	4.0	140°, 77°	025°, 05°	308°, 12°	LPS
SFD-10-14.3	N40°E, 25°S	UP	49	0.0	157°, 53°	029°, 20°	296°, 30°	LPS
SFD-11-3	N90°E, 40°S	UP	30	3.3	176°, 07°	359°, 43°	268°, 02°	LPS
SFD-11-4	N35°E, 45°S	UP	18	0	144°, 13°	284°, 73°	054°, 01°	LPS
SFD-11-5	Horizontal	UP	36	5.5	167°, 73°	002°, 17°	270°, 04°	LNS
SFD-11-6	Horizontal	UP	36	8.3	002°, 12°	154°, 78°	271°, 06°	LPS
SFD-11-7	N70°E, 50°S	UP	26	11.5	177°, 65°	339°, 26°	074°, 07°	LPS
SFD-11-8	N70°E, 55°N	UP	20	5	076°, 10°	346°, 02°	245°, 80°	LPS
SFD-11-9	Horizontal	UP	22	4.5	350°, 17	180°, 73°	080°, 02°	LPS
SFD-11-9V	N40°W, 90° *	UP	14	7.1	306°, 05°	205°, 05°	078°, 83°	LPS
SFD-11-10	N30°E, 45°S	UP	16	6.3	176°, 23°	290°, 41°	066°, 38°	LPS
SFD-11-11	N30°E, 20°NW	UP	19	15.8	073°, 77°	310°, 03°	218°, 09°	LNS
SFD-11-12	N40°E, 45°S	UP	36	25	188°, 51°	003°, 68°	042°, 5°	LPS
SFD-11-12V	N40°W, 90° *	UP	34	5.9	138°, 01°	228°, 08°	049°, 82°	LPS
SFD-11-13	N40°E, 90°	UP	30	13	265°, 03°	166°, 74°	357°, 16°	LPS

*Table 1. Calcite Twinning Strains. All samples are from within the Sundance Fm. Sample names that include a V suffix are calcite veins from within the Sundance Fm. * = vein orientation rather than bedding orientation. UP= upper plate. LP = lower plate. n= number of twinned grains measured in a thin section. PEV= positive expected value. NEV= negative expected value. e1= maximum compression shortening axis. e2= intermediate axis. e3= extension axis. LNS= layer-normal shortening. LPS= layer-parallel shortening.*

SFD-10-5.1 is the only sample that has almost 40% NEVs (37.5%), which can be considered to indicate a secondary, non-coaxial twinning deformation. While the primary strain is a LPS fabric, with the shortening axis trending NE, the NEV overprint preserves LNS, and trends NW. This LNS overprint could be due to shortening as the detachment settled in a lower paleovalley, where it currently lies, after travelling from the NW. SFD-11-5 and SFD-11-11 preserve LNS and have a low percentage of NEVs (10.7%).

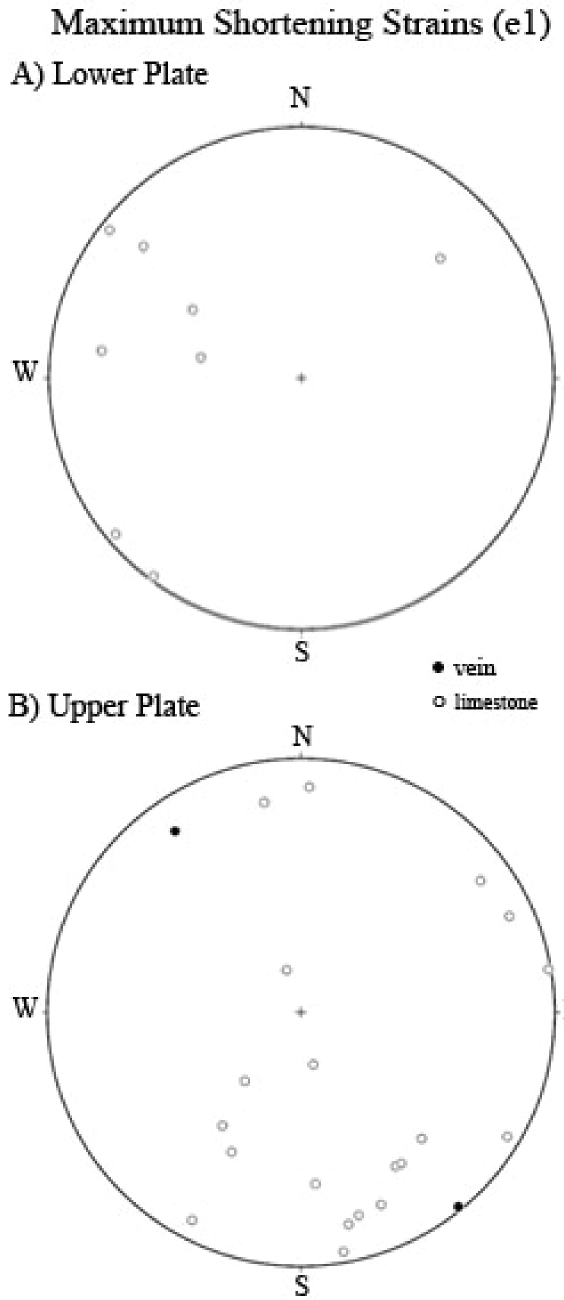

Figure 3. Plots of e1 (maximum compression shortening axes) after rotation of bedding to original horizontal position in A) Upper Plate and B) Lower Plate. ◦= limestone , • = vein.

Calcite Veins

Although the two calcite veins analyzed are from different locations within the upper plate, their twinning strain results are nearly identical (Table 1). Bedding is horizontal, vein orientations are the same (vertical and trending N40°W) and they each exhibit LPS with shortening axes trending to the NW-SE with very shallow plunges.

DISCUSSION

The twinning strain present in the Sundance Fm. is likely due to a Sevier-Laramide orogen triaxial compressive stress (E-W), and would have subsequently experienced rotation, but no secondary twinning, while remaining parallel to bedding during the Eocene detachment. The low percentage of NEVs and a disorderly arrangement of shortening axes in the upper plate (Fig. 3) support the interpretation of the South Fork allochthon as a detachment. Since twinning along either of the remaining two e{0112} glide planes requires higher stress levels and an orientation of >45° from the stress orientation that caused previous twinning (Teufel, 1980), it is not surprising that emplacement of the South Fork allochthon could have occurred without a twinning overprint or any additional macroscopic deformation. Twinning in calcite is time-dependent, and once twinned, calcite strain hardens making a twinning overprint difficult.

My interpretation is then, that the Sundance Fm. limestones preserve a layer-parallel shortening strain of Sevier-Laramide origin, which was passively transported into what is now the upper plate allochthon of the S. Fork detachment system. The SFD offsets Eocene Willwood Fm. sediments and is overlain by the Deer Creek member of the Wapiti Fm., and the radiometric ages of each (See Schroeder, Kelly, MacNamee, this volume) unit constrain the age of the motion of the SFD allochthon to a brief window between ~53 and 48.9 Ma. It is easier to attribute the structures and calcite twinning story to a large landslide allochthon that moved ~10 km, rather than invoke a separate, local orogenic event with its own deformational history. Additional evidence is the 2 calcite veins (N40W) in upper plate Sundance limestones that preserve a NW-SE shortening strain, presumably parallel to the allochthon transport direction.

CONCLUSIONS

Nearly all samples in the Jurassic Sundance Formation of the South Fork detachment preserve a layer-parallel, or sub-horizontal, shortening fabric. This fabric has, however, been reoriented due to rotation of the shortening axes, which are chaotic. Minimal negative expected values indicate only one major deformational twinning episode and no strain overprint. Considering previous research, field relationships, and the presence of a reoriented twinning strain without substantial secondary twinning, it seems evident that the South Fork allochthon formed as a landslide allochthon in the Eocene.

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REFERENCES

Beutner, E.C. and Hauge, T.A., 2009, Heart Mountain and South Fork fault systems: Architecture and evolution of the collapse of an Eocene volcanic system, northwest Wyoming. Rocky Mountain Geology, v. 44, no. 2 p. 147–164.

Blackstone, D. L., Jr., 1985, South Fork detachment fault, Park County, Wyoming: Geometry, extent, source: Contributions to Geology, University of Wyoming, v. 23, p. 47–62.

Clarey, T. L., 1990, Thin-skinned shortening geometries of the South Fork fault: Bighorn Basin, Park County, Wyoming: The Mountain Geologist, v. 27, p. 19–26.

Clarey, T.L., 2008, The break-away point of the South Fork Superfault; a catastrophic gravity slide, Wyoming, USA: Abstracts with Programs - Geological Society of America, v. 40, p. 312-313.

Clarey, T.L., 2009, Timing relations between the South Fork and Heart Mountain Fault systems with implications for emplacement, Wyoming, USA: Abstracts with Programs - Geological Society of America, v. 41, p. 570-570.

Craddock, J.P., Malone, D.H., Cook, A.L., Rieser, M.E., and Doyle, J.R., 2009, Dynamics of emplacement of the Heart Mountain allochthon at White Mountain: Constraints from calcite twinning strains, anisotropy of magnetic susceptibility and thermodynamic calculations: Geological Society of America Bulletin, v. 121, n. 5, p. 919-938.

Feeley, T.C., and Cosca, M.A., 2003, Time vs. Composition Trends of magmatism at Sunlight Volcano, Absaroka Volcanic Province, Wyoming: Geological Society of America Bulletin, v. 115, p. 714-728.

Groshong, R.H., Jr., 1972, Strain calculated from twinning in calcite: Geological Society of America Bulletin, v. 83, 2025-2038.

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

Kravitz, K., 2011, Insights into the origin of the South Fork Detachment, Wyoming, using calcite strain analysis. Keck research symposium in Geology Proceedings, 24, 351-357.

Kravitz, K., 2011. Insights into the origin of the South Fork Detachment, Wyoming, using calcite strain analysis [B.S. thesis]: Smith College, 63 p.

MacNamee, A., Kravitz, K., Kenderes, S., Mathisen, M., Malone, D.H., and Craddock, J.P., 2011, New Insights on the structural evolution of the Eocene South Fork detachment: Abstracts with Programs - Geological Society of America, v. 43, no. 5, p. 115.

Malone, D.H., and Craddock, J.P., 2008, Recent contributions to the understanding of the Heart Mountain Detachment, Wyoming: Northwest Geology, v. 37, p. 21-40.

Pierce, W.G., 1957, Heart Mountain and South Fork detachment thrusts of Wyoming: American

Association of Petroleum Geologists Bulletin, v. 41, p. 591-626.

Pierce, W.G., and Nelson, W.H., 1968, Geologic map of the Pat O'Hara quadrangle, Park County, Wyoming: U.S. Geological Survey Quadrangle Map GQ-755, Scale: 1:62,500.

Pierce, W.G., and Nelson, W.H., 1969, Geologic map of the Wapiti Quadrangle, Park County, Wyoming: U.S. Geological Survey Quadrangle Map GQ-778, Scale: 1:62,500.

Pierce, W.G., 1986, The South Fork detachment fault, Park County, Wyoming: Discussion and reply: Contributions to Geology, v. 24, p.77-90.

Rhodes, M.K., Malone, D.H., Carroll, A.R., and Smith, M., 2007, Sudden Desiccation of Lake Gosiute at 49 Ma: A Downstream Effect of Heart Mountain Faulting? The Mountain Geologist, v. 1, p 1-10.

Smith, M.E., Singer, B., and Carroll, A.R., 2003, 40Ar/39 Ar geochronology of the Green River Formation, Wyoming: Geological Society of America Bulletin, v. 115, p. 549-565.

Teufel, L.W., 1980, Strain analysis of experimental superposed deformation using calcite twin lamellae: Tectonophysics, v. 65, p. 291-309.van der Pluijm, B.A., and Marshak, S., 2004, Earth Structure: An Introduction to Structural Geology and Tectonics, 2nd Edition: W.W. Norton, & Co., 656 p.