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Calcite twinning strain constraints on the emplacement rate and kinematic pattern of the upper plate of the Heart Mountain Detachment

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Abstract

Two models that address the emplacement rate of the upper plate of the Heart Mountain Detachment (HMD) have been advanced. These are the catastrophic tectonic denudation model and the slow, incremental continuous allochthon model. We compared the two models by analyzing upper and lower plate rocks for a detachment-related overprint of the older, layer-parallel Laramide–Sevier calcite twinning strain fabric. Lower plate Pilgrim Limestone samples, even those collected a few meters below the detachment, show no evidence of a detachment-related twinning strain overprint (negative expected values, NEVs, avg. 8.3%) of the Laramide–Sevier layer-parallel fabric. The allochthonous upper plate carbonate rocks preserve the layer-parallel Laramide–Sevier shortening strain, but the shortening axis (e_1) for each block occurs in different, non-EW and both subhorizontal and non-subhorizontal orientations. For the six upper plate blocks that preserve chaotic shortening axis orientations, no evidence of any detachment-related twinning strain overprint (NEVs avg. 7.5%) was found. In the absence of any HMD-related twinning overprint, the upper plate allochthon motion must have been rapid enough to be accommodated by fracturing of upper plate rocks without additionally twinning any calcite. We conclude that the emplacement of the upper plate of the HMD was not accompanied by an overprint of the Laramide–Sevier twinning fabric and that models that require catastrophic, rather than slow, incremental emplacement rates are best supported by these data.

1. Introduction

The Heart Mountain Detachment (HMD) has been one of the most enigmatic features in North American structural geology for nearly a century. The major characteristics of the HMD as summarized by Pierce (1973) (see also Hauge, 1993) are: (1) a dispersed (>3400 km^2 in area) upper plate consisting of dozens of mountain-sized (and many hundreds of smaller) remnants, some of which were transported at least 30 mi (50 km); (2) a detachment horizon that consistently lies along a lower Ordovician bedding plane; (3) an average dip of the detachment horizon at the time of emplacement of less than 2°; and (4) a breakaway, bedding plane, transgressive ramp, and former-land-surface phase, with a younger-over-older age relation in the bedding plane area and an older-over-younger age relation in the transgressive ramp and former-land-surface area. Movement along the HMD was broadly contemporaneous with the inception of widespread igneous activity in the Absaroka Volcanic Province. Absaroka (Eocene) volcanic rocks currently both overlie and fill areas between allochthonous Paleozoic rocks and contain petrified wood. The age of Heart Mountain faulting is well understood and widely accepted. Stratigraphic evidence from Eocene sedimentary and volcanic rocks (Pierce, 1973, 1987; Torres and Gingrich, 1983) indicate that the emplace-

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ment of the Heart Mountain detachment upper plate occurred within a 2 My window during the early middle Eocene (49.5–47.5 My ago). Fission track uplift studies of the Rattlesnake Mountains indicate that this range was a topographic barrier (Laramide) that was a buttress that formed the transgressive ramp of the HMD (Omar et al., 1994).

The mechanical enigma posed by the classic (e.g. Pierce, 1973) view of mountain-sized, coherent blocks sliding down a detachment plane with an average dip of less than 2° for distances as great as 30 mi (50 km) with gravity as the sole driving mechanism has put the HMD at the center of the debate over the mechanical paradox of low-angle normal faulting. Several aspects concerning the origin of and movement along the HMD are presently in dispute: These include: (1) the emplacement rate of the upper plate; (2) the dispersal and kinematics of the upper plate; (3) the degree and nature of involvement of volcanic rocks in faulting; and (4) the emplacement mechanism of the upper plate that facilitated movement down a very gentle slope without the aid of a push from the rear. Among these many areas of dispute, the emplacement rate of the allochthons along the detachment has been particularly difficult to quantify and constrain.

Models that explain the emplacement rate of the upper plate of the HMD fall into two broad categories: (1) catastrophic emplacement; or (2) slow, incremental emplacement. For many years, the upper plate of the HMD was viewed to have been emplaced catastrophically as numerous, independently moving slide blocks (Bucher, 1936; Hughes, 1970; Pierce 1973, 1987; Voight, 1974; Prostka, 1978; Malone, 1993), and as a result of this detachment faulting, a tectonically denuded surface was formed. Immediately after faulting had ceased, massive, incremental outpourings of Wapiti Formation volcanic rocks (Pierce, 1973, 1987), or a large debris–avalanche deposit (Malone, 1993) buried the detached blocks as well as the intervening tectonically denuded surface. Other catastrophic emplacement models that do not require tectonic denudation have been advanced by Sales (1983) and Beutner and Craven (1996).

Alternatively, Hauge (1982, 1985, 1990) interpreted the upper plate of the HMD to have been emplaced gradually rather than catastrophically. Hauge, like Sales (1983) and Beutner and Craven (1996) envisioned a single, continuous allochthon composed largely of Eocene volcanic rocks, rather than numerous individual slide blocks as had been previously postulated. In the context of his 'continuous allochthon' model, the ideas of catastrophic emplacement rates no longer were necessary, since no denudation would have occurred. Instead displacement could have been more gradual, occurring over one million or more years (Hauge, 1990), and coeval with Absaroka volcanism that produced the bulk of the volume of the allochthon and contributed to the gravitational instability responsible for its movement. Templeton et al. (1995) cite O and C isotope depletions in the Heart Mountain fault breccia from the break-away area, as compared to the distal areas of the detachment, as evidence in support of the continuous allochthon model.

The development of the slow, incremental movement model has led to the present problem: What was the emplacement rate of the upper plate? Was it emplaced catastrophically over a few minutes or hours or was it emplaced gradually over a million or more years? The goal of this investigation was to utilize the presence of a pre-HMD Laramide–Sevier twinning strain fabric as a guide to interpreting subsequent deformation within upper and lower plate carbonate rocks that were associated with translation during emplacement, thereby documenting detachment-related strain overprints, and the rotational motion of the upper plate blocks, if any. The presence or absence of subsequent overprints of detachment-related twinning strain within upper and lower plate carbonate rocks might also constrain the emplacement rate, as per this end-member hypothesis: Because calcite twinning is strain-rate dependent (a critical resolved shear stress at or above the yield stress for twinning must be applied for a duration of time), catastrophic emplacement of the upper plate of the HMD would involve a dramatic stress and strain field change (triaxial to uniaxial conditions) but would not involve any detachment-related strain overprint of the older, strain-hardened Sevier–Laramide twinning fabric because the upper plate motion was too rapid. Conversely, a changing triaxial stress and strain field (orientation and magnitude) is required by a slow, incrementally emplaced allochthon, and the Laramide–Sevier twinning fabric in both the upper and lower plate of the HMD should show a detachment-related overprint if this model is correct.

Our study documents the calcite twinning strain fabric for 11 upper (ten limestones, one vein) and 12 lower (seven limestones, five veins) plate samples (23 total) from much of the HMD area and discusses the bearing of these data on the emplacement rate and dispersal pattern of the upper plate allochthons (Table 1, Fig. 1). This is the only study to our knowledge that uses calcite twinning fabric analysis as a speedometer for deformation rates.

2. Results

2.1. Calcite twinning

Calcite twins mechanically at low differential stresses where the critical resolved shear stress is ~100 bars (see LaCombe and Laurent, 1996; Ferrill, 1998) and is largely independent of temperature and normal stresses in the upper 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 only at higher stress levels if that compressive 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; 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., 1996); reports of twinning strains in rocks of extensional regimes (Iceland, Alaska) are limited and these rocks preserve sub-horizontal shortening fabrics (Craddock et al., in review; Craddock and Grischkowsky, in review). 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, and De Bresser and Spiers (1997) have noted the importance of other slip systems (r, f, etc.) in calcite under varying experimental conditions.

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 gauge (Groshong, 1972, 1974) and are quite accurate for strains ranging from 1–17% (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 (~0.5–5.0 μm) are dominant in our sample suite, which is characteristic of calcite deformed below 200°C (Ferrill, 1991, 1998) and we used an average value of 1.5 μm in our computations. The calcite strain gauge technique also computes negative and positive expected values (NEV and PEV, 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 independently (Teufel, 1980). On a stereographic projection, the intersection of the shortening axis (e_1) and contoured maxima of the compression axes, with the bedding orientation of the sample is interpreted to be a layer-parallel shortening strain.

2.2. Pre-detachment Sevier–Laramide strains

Motion along the HMD occurred during the

Table 1
Calcite twin analysis[a]

Sample	$n=$	Upper, Lower, Vein	Bedding strike and dip	Vein strike and dip	e_1 Trend, Plunge (°)	e_1 (%)	NEV (%)	Location (Strat. unit)
1	26	upper	Horizontal	None	44°,5°	−2.4	13	Sunlight Creek (M)
2	25	upper	Horizontal	None	274°,4°	−3.5	11	Steamboat (M)
3	36	upper	N30°W, 80°E	None	43°,82°	−7.6	10	Dead Indian Pass (M)
4	25	upper	Horizontal	None	6°,5°	−3.8	4	Steamboat (M)
5	17	upper	Horizontal	None	286°,7°	−4.5	0	Heart Mountain (M)
6	18	upper	N10°E, 15°W	None	291°,4°	−3.2	6	Heart Mountain (M)
7	28	upper	N30°W, 47°W	None	244°,65°	−3.1	0	Logan Mountain (M)
8	26	upper	N2°E, 68°W	None	112°,6°	−5.1	10	Logan Mountain (M)
9	13	upper	N5°W, 46°W	None	292°,54°	−1.1	7	Sheep Mountain (M)
10	14	upper	Horizontal	None	357°,2°	−2.8	0	Sheep Mountain (M)
11	27	lower	Horizontal	None	84°,10°	−3.2	8	Beartooth Butte (C)
12	25	lower	Horizontal	None	262°,1°	−5.5	4	Dead Indian Pass (C)
13	23	lower	Horizontal	None	274°,13°	−5.5	21	Dead Indian Pass (C)
14	28	lower	Horizontal	None	106°,17°	−6.4	0	Steamboat (C)
15	18	lower	Horizontal	None	289°,4°	−5.8	15	Steamboat (C)
16	14	lower	Horizontal	None	88°,2°	−5.8	0	Steamboat (C)
17	21	lower	Horizontal	None	273°, 5°	−4.7	8	White Mountain (O)
18	12	vein, lower	Horizontal	N–S, 90°	194°,7°	−3.9	22	Rattlesnake Mountain (O)
19	18	vein, lower	Horizontal	N15°E, 90°	12°,20°	−1.7	12	Steamboat (C)
20	11	vein, lower	Horizontal	N70°W, 90°	198°,83°	−8.6	100	Steamboat (C)
21	26	vein, lower	Horizontal	N70°W, 90°	285°, 7°	−7.5	0	Steamboat (C)
22	26	vein, lower	Horizontal	Horizontal	6°, 85°	−7.2	8	White Mountain (O)
23	32	vein, upper	Horizontal	N10°E, 90°	240°,22°	−8.5	16	Steamboat (M)

[a] Key: C = Cambrian limestones; O = Bighorn Dolomite; M = Miss. Madison Grp.; n = number of grains; e_1 = shortening axis; NEV = negative expected values.

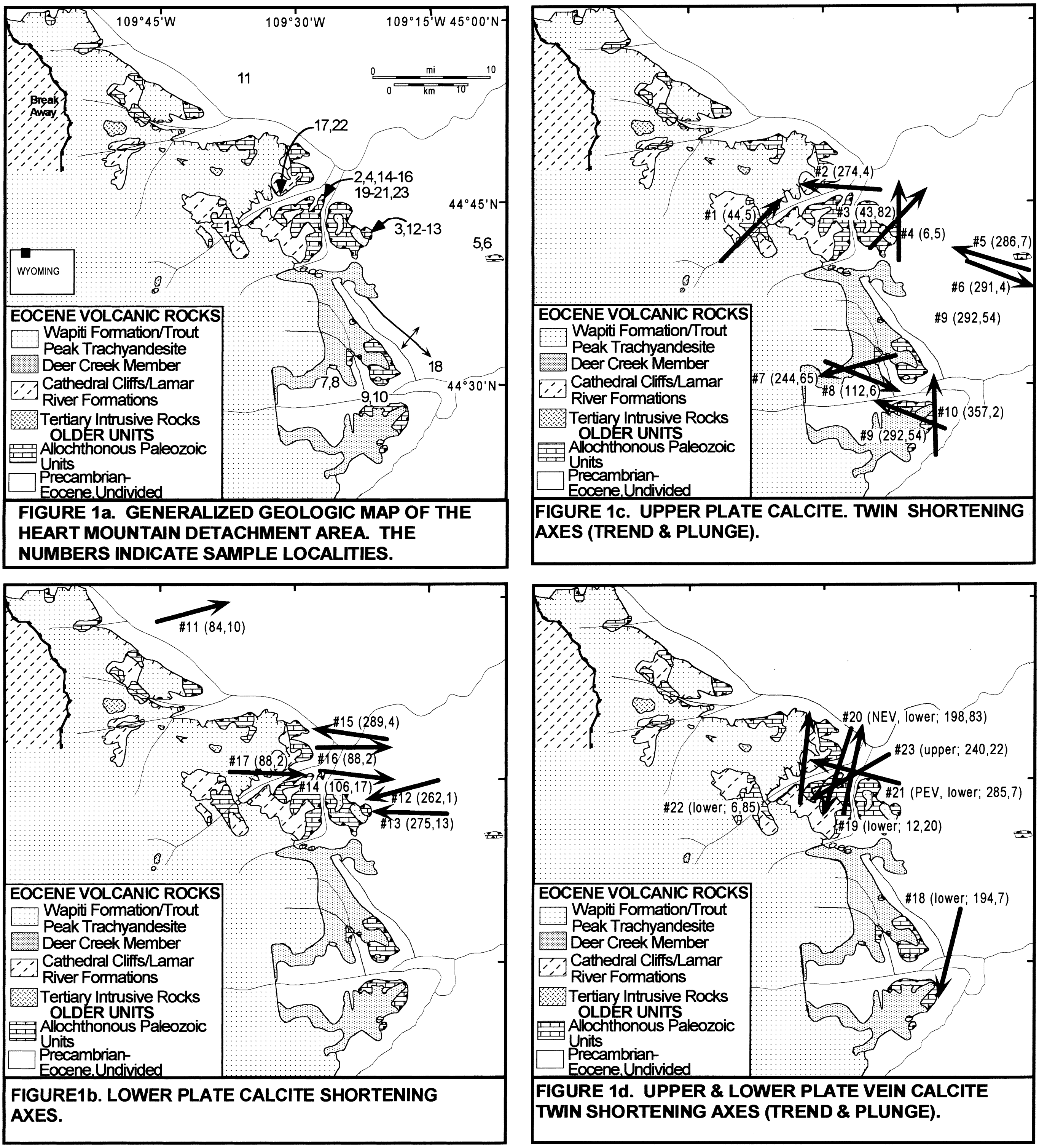

Fig. 1. (a) Regional geology of the Heart Mountain detachment area and sample sites and numbers for calcite twinning data. (b) Lower plate calcite twin analysis results. Each line represents the maximum shortening strain axis (e_1). Sample sites are numbered (a) and keyed to Table 1. (c) Upper plate maximum shortening strain axis data, including plunges and sample site numbers. All samples preserve bedding-parallel shortening. (d) Vein shortening strain axes, with upper and lower plate indicated, as well as sample number and plunge.

Eocene, meaning that any rocks deposited and buried in this area before ~50 Ma could preserve a Sevier–Laramide orogen (Armstrong and Oriel, 1965; Wiltschko and Dorr, 1983; Craddock, 1992) tectonic rock fabric. The presence of such a regional layer-parallel, thrust transport-parallel (E–W) shortening strain fabric, as preserved by mechanically twinned calcite in limestones, is found throughout the thin-skinned Mesozoic Sevier orogen in the Idaho–Wyoming thrust belt (Craddock, 1992), the younger Laramide orogen thick-skinned uplifts and eastward into the cratonic foreland (Craddock et al., 1993; Craddock and van der Pluijm, 1999). The layer-parallel shortening fabric is interpreted to be a pre-thrust translation fabric as it is everywhere bedding-parallel and E–W in orientation in the autochthonous foreland (Craddock and van der Pluijm, 1999), and bedding-parallel, but slightly rotated from E–W, in the western, allochthonous regions where there is no Basin and Range extensional overprint (Craddock, 1992). This regional fabric is then a passive strain marker that can be used in tracking the motions of rocks whose allochthonous motions post-date the mechanical twinning.

2.3. Lower plate

The autochthonous Cambrian carbonates below the HMD also preserve this layer-parallel pre-detachment strain (e_1 is $\pm 20^\circ$ to bedding) but, as these rocks are autochthonous, the shortening axes are oriented approximately E–W (Fig. 1b; average shortening axis is N94°E with various shallow plunges). There is no detachment-related twinning strain overprint in these rocks as none of the samples have any significant NEVs (Table 1).

2.4. Upper plate

Ten samples from six different localities of HMD upper plate allochthons preserve the pre-HMD, layer-parallel shortening strain fabric (e_1 is $\pm 20^\circ$ to bedding), but occur in a variety of non-EW orientations (Fig. 1c). Within localities where there are multiple strain analyses (samples 2, 4, and 10), there are also multiple orientations of the layer-parallel shortening strain axis within a given locality, indicating that these components of the upper plate are not everywhere in a simple, upright position but have suffered internal dismemberment and rotation. There is no detachment-related twinning strain overprint in these rocks as the NEVs are minimal (Table 1).

2.5. Veins

Six veins (five lower plate, one upper plate) were analyzed and recorded six strain results (Fig. 1d; Table 1). Four of the twinning strain results indicate that vein-parallel and northerly sub-horizontal shortening has occurred and we presume these are pre-detachment Laramide veins (see van der Pluijm and Craddock, 1996; Craddock and van der Pluijm, 1999). A vein from the Cambrian Pilgrim Limestone below Steamboat in the transverse detachment ramp, and within 30 m of the HMD, preserved a high percentage of NEVs, such that we split the data (samples 20, 21). The PEV-split (sample 21) preserves vein-parallel shortening, while the secondary NEV-split (sample 20) preserves a vertical loading overprint. One calcite vein (sample 22) that is 1.6 m below, and parallel to, the detachment (Ed Beutner, personal communication) preserves a vertical shortening strain and no overprint (8% NEVs). The inferred differential stress responsible for this twinning is ~34 MPa (Jamison and Spang, 1976).

Within the vein suite, sample 22 is likely to be a syn-detachment vein and its twinning strain result can be interpreted relative to the dynamics of the detachment. The remaining veins (18, 19, 21 and 23) are probably pre-detachment veins, allowing us to use the NEV-split overprint (vertical shortening) strain in sample 20 relative to interpreting the detachment kinematics. Is the vertical shortening axis in samples 20 and 22 (NEV) the result of the horizontal motion of the upper plate, or the result of the vertical lithostatic load imposed on the lower plate after the HMD upper plate stopped moving?

3. Discussion

3.1. Constraints on detachment-related deformation

The absence of detachment-related calcite strain overprints provides the possibility that calcite twinning as a deformation mechanism could provide a constraint on the motion of upper plate allochthons of the HMD as twinning is a time-dependent deformation mechanism. The carbonate rocks involved in the HMD event contain an older, pre-detachment twinning strain that makes interpreting the kinematic pattern of the upper plate allochthons possible. Interpreting the detachment kinematic pattern is complicated because calcite strain hardens when twinned, and causing calcite to twin a second time, especially under uniaxial conditions (upper plate allochthons sliding downhill), is not constrained by experimental or empirical data.

3.2. Uniaxial vs. triaxial constraints

The dichotomy we have in using calcite twinning as a means to interpret the HMD dynamics is that the pre-HMD twinning fabric formed under an orogenic triaxial stress state, and that a twinning overprint would have been acquired under uniaxial conditions (no confining pressure, see below) while the upper plate allochthons were emplaced. Pure calcite twins readily, under uniaxial conditions, in the palm of your hand with a properly applied thumbnail (Turner et al., 1954). Calcite also fractures readily, with no twinning overprint, when subjected to a uniaxial dynamite blast (e.g. in a road cut). Unfortunately, the results of uniaxial experiments on previously deformed (twinned) carbonates under triaxial conditions have never been reported (H. DeBresser, personal communication, 1999); Teufel (1980) studied twinning strain overprints in limestones deformed under numerous axial loading conditions, all under triaxial stress conditions. Friedman and Heard (1974) also demonstrated that twinning in Cretaceous limestones started within 10 min of triaxial creep tests with various loads (compression and tension), confining pressures and temperatures.

Calcite is known to strain harden once it twins mechanically, and to superimpose a second, younger twinning strain requires a high differential stress (~50 MPa) applied at a low strain rate oriented ~45–90° to the compressive stress field (σ_1) that caused the primary twinning strain (Teufel 1980). The rocks studied here, based on the results of van der Pluijm et al. (1997), would have been twinned initially by a sub-horizontal, E–W compressive stress with a magnitude of ~90 MPa. When a sample has a high percentage of NEVs (> 40%), it is likely that a subsequent twinning strain has occurred. Our upper and lower plate samples have no HMD-related twinning overprint (NEVs < 8%), contain numerous untwinned grains (~20%) and an increasing density of fractures close to the detachment.

3.3. Constraints on the emplacement rate of the upper plate allochthons

As the upper plate was emplaced down slope, it is likely that it was under uniaxial conditions, where the dominant internal stress was the vertical lithostatic load (~20 MPa at the detachment); this would have been oriented ideally for extensional overprinting perpendicular to the stress field responsible for the earlier Sevier–Laramide twinning fabric (i.e. sub-horizontal and ~E–W trending). If subsequent movement occurred over many thousands of years (Hauge, 1985), with or without significant confining pressure, some calcite somewhere in the upper plate must have twinned or retwinned. In the absence of any HMD-related overprint, motion of the upper plate allochthons must have been rapid enough for the fracturing of rocks along the detachment (high strain rate) without twinning or retwinning any calcite (no differential stress or confining pressure; see Twombly and Spang, 1982).

The HMD is characterized by a highly fractured fault zone, syn-detachment calcite veins, the absence of a twinning strain overprint, localized pseudotachylite (Beutner and Craven, 1996; Beutner, personal communication, 1998), and a maximum time of about 2 Ma (Pierce, 1973) for the deposition/eruption of the involved volcanic rocks and the emplacement of the upper plate. These observations are supportive of a catastrophic (Bucher, 1936; Pierce, 1973, 1987; Hughes, 1970; Voight, 1974; Prostka, 1978; Malone, 1994; Beutner and Craven, 1996) rather than gradual (Hauge, 1985, 1990) emplacement of the upper plate allochthons of the HMD.

What, then would be the explanation of the vertical shortening strain preserved in the detachment-parallel calcite vein (sample 22) and the NEV vertical shortening strain overprint (sample 20) in the adjacent lower plate? If the emplacement of the upper plate allochthons was free of additional twinning, then the vertical shortening strain is likely to be a result of the post-detachment lithostatic load of the upper plate overburden. The inferred differential stress responsible for the twinning strain in sample 22 is 34 MPa (Jamison and Spang, 1976), in which σ_1 was oriented vertically. The preserved thickness of the upper plate at White Mountain, where sample 22 was collected (E. Beutner, personal communication, 1998), is ~900 m, giving a lithostatic load of ~23 MPa (see Wiltschko and Sutton, 1982). The true thickness of the upper plate in the Eocene was probably closer to 1300 m, where the vertical stress would have been closer to 34 MPa. Sample 20 (NEV) was collected ~30 m below the detachment at Steamboat in the Pilgrim Limestone. The vertical shortening and compression in this sample is also likely the result of the post-detachment loading, as this vein is coarse grained and fairly close to the detachment. The primary twinning strain in the vein sample suite is a vein-parallel, northerly and sub-horizontal shortening fabric with inferred differential stress magnitudes of ~70 MPa. This is a common Sevier–Laramide vein twinning strain fabric (Craddock and van der Pluijm, 1999), and probably pre-HMD, making samples 20 (NEV) and 22 uniquely related to the HMD dynamics.

3.4. Kinematic pattern of the upper plate allochthons

Our study also provides the first evidence that the motion of the Paleozoic rocks that slid along the HMD did so rotating about a vertical axis. Most of these allochthonous Paleozoic rocks are flat-lying and upright although bedding dips of 60–80° are observed, indicating a more complex rotation during motion. Our data document upper plate motions relative to the fixed reference of the autochthonous lower plate calcite twinning fabric (~E–W, sub-horizontal; Fig. 1b), constraining upper plate motion ±90° for those upper plate localities that have a sub-horizontal e_1 shortening axis. Where the bedding plane portion of the detachment is exposed, striations and grooves are oriented S55°E (Malone et al., 1999, fig. 8) and are often preserved in a thin (5 mm) veneer of microbreccia (Gerbi, 1997; Ulstad, 1998; Colgan, 1998; Ed. Beutner, personal communication, 1999; Malone et al., 1999), which is ~3 m thick at White Mountain and could be classified as a carbonate pseudotachylite. Unfortunately, we are unable to reconstruct the path or number of rotations of individual localities from the lower plate reference. As an example, for the former land surface portion of the detachment, the difference between the shortening axes of the lower plate (~E–W, 0° average; range of N71°W, 0° to S72°W, 0°) and Heart Mountain axis (~N72°W, 5°) is ~20°. Heart Mountain could have moved in a linear path to the southeast and rotated 20° clockwise (or, 160° counterclockwise) to its current position. Conversely, the possibility exists that Heart Mountain could have rotated an infinite number of times about a vertical axis coming to rest ~N72°W. The other end member could have involved the above scenario, but with a non-linear translation from Heart Mountain's initial to current location. Sample 1, from the bedding-plane portion of the detachment, has rotated 46° counterclockwise (or, 326° clockwise; e_1 of 44° from a starting orientation of 90°) while moving along the detachment to the southeast (detachment striations S55°E). Complex vertical rotations of the upper plate blocks have been documented by paleomagnetic studies of Eocene plutonic rocks where the paleopoles of seven sites are different, and none correlate with a fixed Eocene paleopole (Gerbi, 1999).

Hauge (1990) indicated that the development of the gradually emplaced 'continuous allochthon' was accommodated by the translation and rotation of upper plate rocks along listric normal faults that were rooted along the detachment. Beutner and Craven (1996) performed a kinematic analysis of the upper plate faults initially described by Hauge (1985); the analysis of the upper plate faults indicated a dominant ESE transport direction for the upper plate. In this scenario, the block rotations largely would have been about non-vertical rather than vertical rotational axes as our study indicates (see schematic cross-sections of the continuous allochthon model in Hauge, 1993, figure 1b). Hauge (1985, 1993) reported the existence of some strike-slip and oblique-slip striae along several upper plate faults, and a wide variety of basal striae orientations. These features are consistent with a continuous allochthon that experienced some degree of radial spreading and hence are compatible with the vertical rotational axes constraint advanced here. Other field evidence, such as radial tear faults or numerous faults within the upper plate dominated by strike-slip striae, which would further support and strengthen the argument for a radial spreading continuous allochthon, has not as yet been reported.

The twin data reported here also support models that include tectonic denudation and the free sliding of numerous, separately moving upper plate allochthons (Pierce, 1973; Malone, 1994). The presence of a chaotic arrangement of upper plate shortening strain axes can be attributed to a kinematic pattern of a collapsing, separating, and dispersing of numerous, independently moving allochthons, with some component of rotation (e.g. Sheep Mountain).

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