Brittle Deformation Sequence at Dead Indian Hill & the Heart Mountain Detachment

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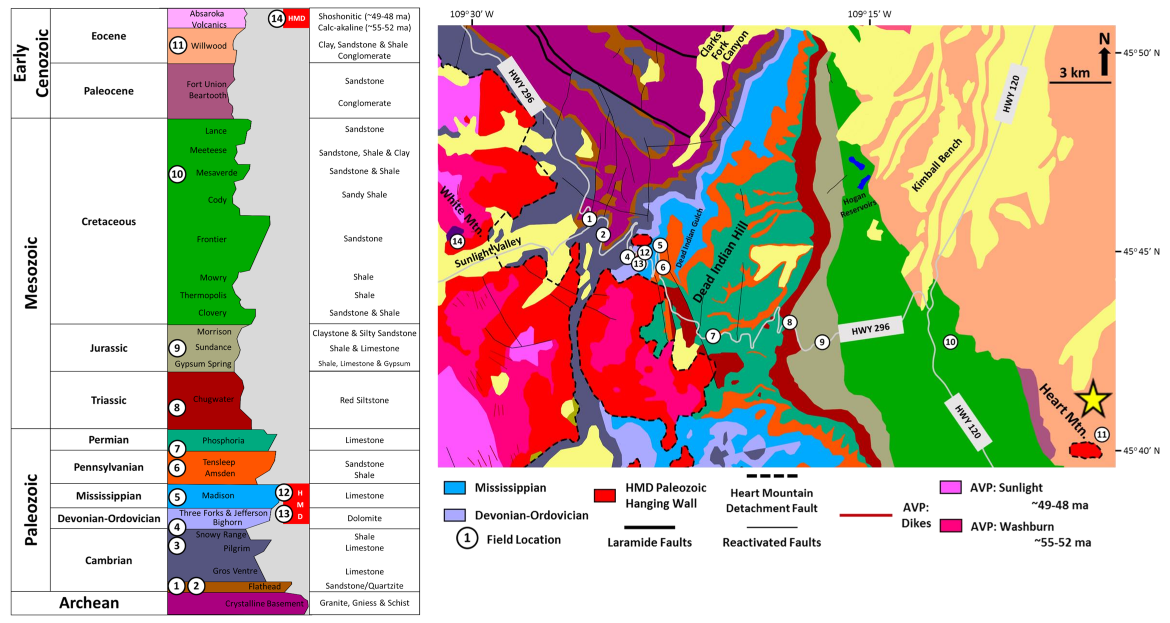
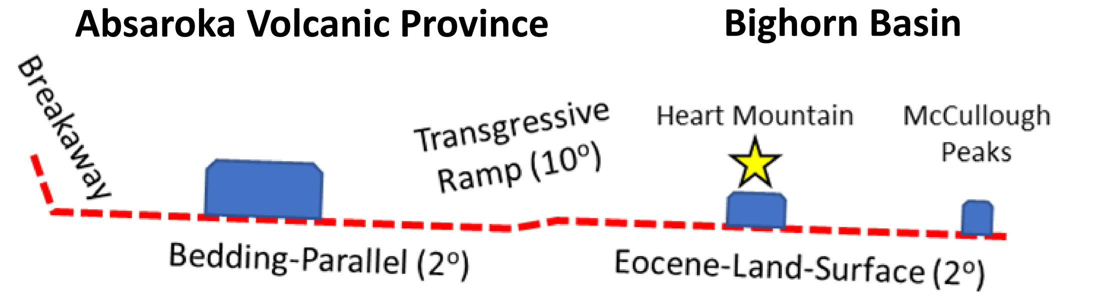
Abstract

The Heart Mountain Detachment in northwestern Wyoming is one of the largest terrestrial mega-scale gravity-slides. Its emplacement followed the Laramide Orogeny and was contemporaneous with the Eocene magmatic activity in the Absaroka Volcanic Province. Analysis of fracture-sets (joints and faults) from Cambrian to Eocene strata provide the framework for deciphering the regional brittle fracture sequence. Measurements are from "pinned to basement" strata below the detachment and a small klippe above the detachment horizon at Dead Indian Hill, the Eocene Willwood Formation in the Bighorn Basin, and the classic White Mountain location.

Laramide fracture-sets at Dead Indian Hill progressively rotate clockwise from north to northeast. The angular and abutting relationships of Laramide joint-sets also occur in the klippe and indicate passive transport of hanging-wall Laramide fracture-sets during the detachment in the Eocene, only after corrections for bedding dip, slope and a clockwise rotation of ~30° around a vertical axis. Laramide fracture-sets were not found in any Eocene age strata.

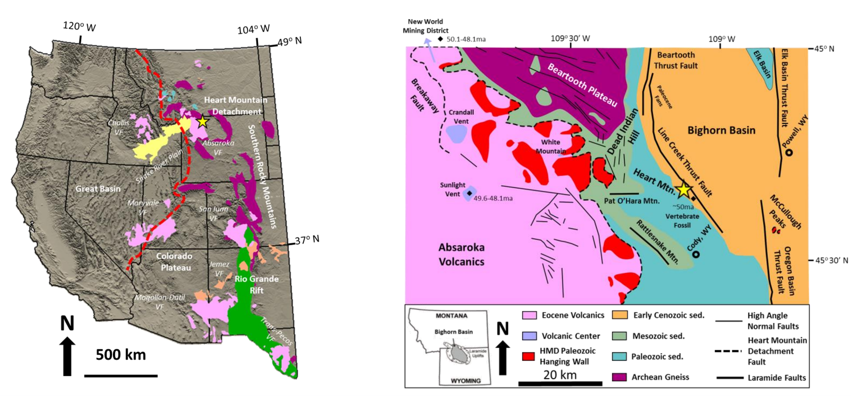
Eocene fracture-sets progressively rotate counterclockwise from the northwest to the west. The Heart Mountain Detachment fractures are defined by joint-reactivations as strike-slip faults which rotate 28° counterclockwise from the oldest Eocene fracture-set.

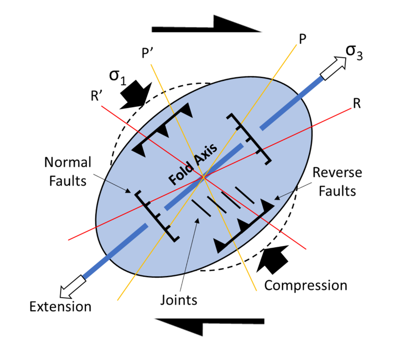


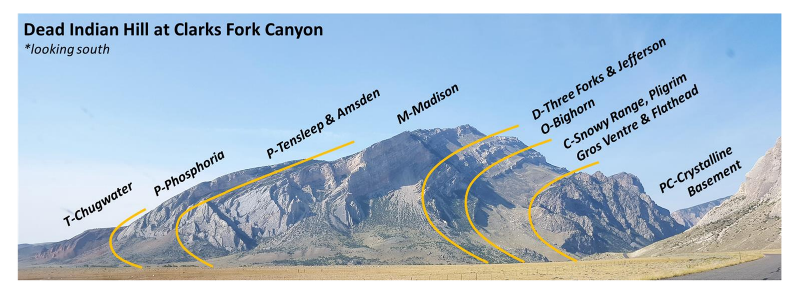


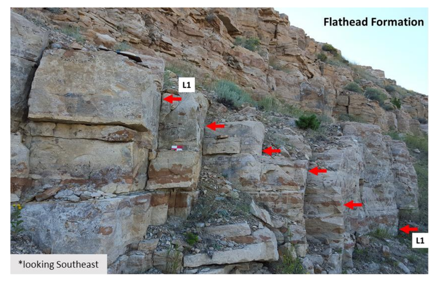
The classic Heart Mountain detachment is categorized as a rootless detachment with a steep dipping breakaway zone, which transitions downward into a low-angle basal decollement within the lower Bighorn Dolomite. The detached mass, once a 1-4km thick package of Paleozoic Carbonates and Volcanic material ~1,100km² in area, had slid along the shallowly inclined surface (~2°) across an aerial extent of ~3,400km² in the Eocene.

*maps modified from Erslev, 1993; Pierce, 1973; Green et al., 1994 *Cross section sketch modified from Goren and Anders 2010







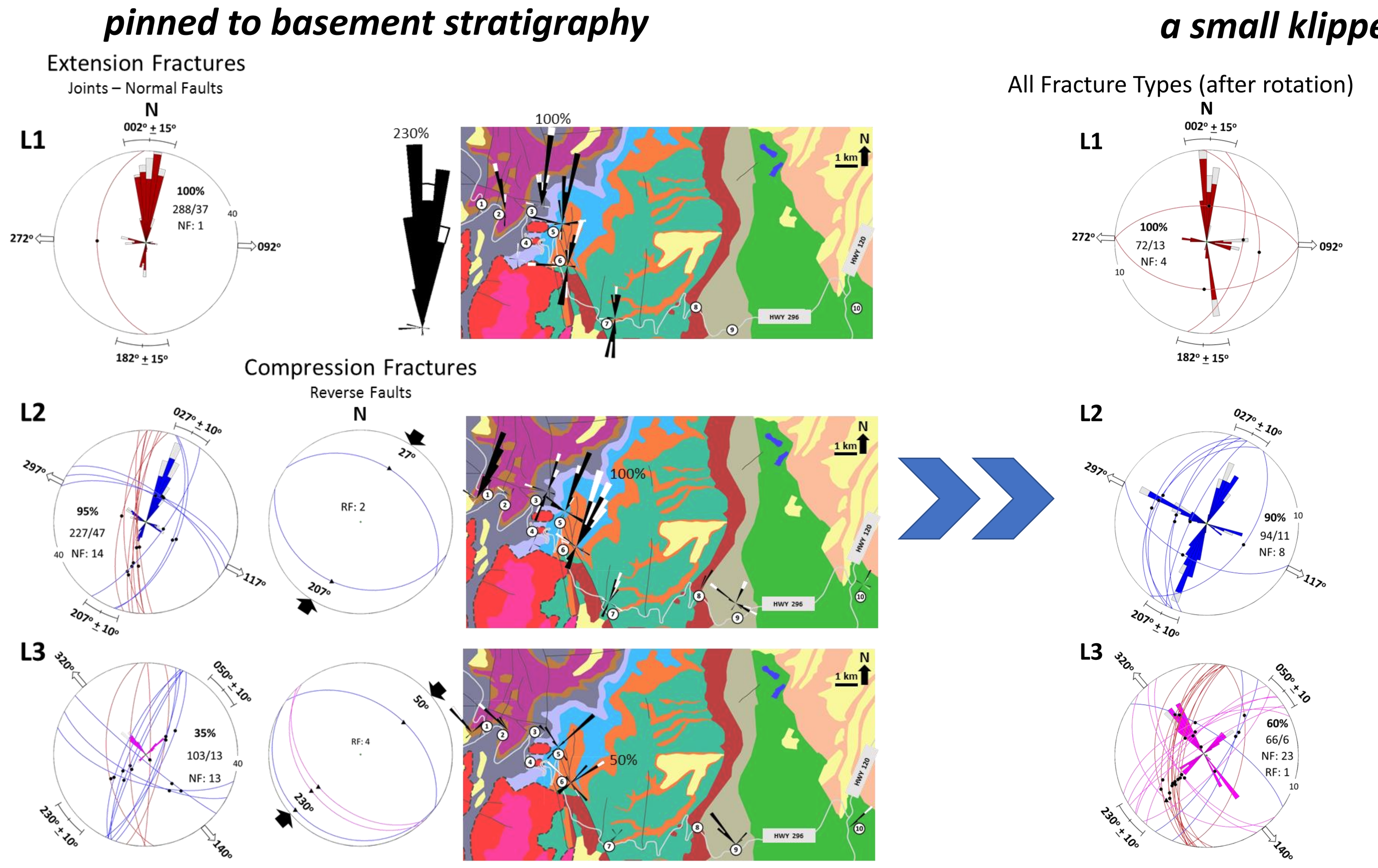


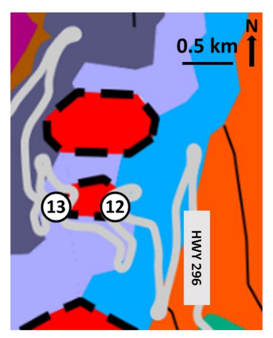
- Anticipated brittle fracture orientations for a hypothetical Right-Lateral shear system.
- East dipping stratigraphy of the basement-cored Laramide Dead Indian Hill Fold at the mouth of the Clarks Fork River Canyon.
- Large en echelon L1-joint in the near flat-lying Flathead Formation in the pinned to basement stratigraphy.
- Although older fracture sets exist in Precambrian granitic rocks beneath the Flathead, they were not evaluated in this study.
- The N-S passive L1 deformation transitions to the bi-modal L2 & L3 active NE-SW compression of the Laramide Orogeny.

Dead Indian Hill Laramide Fracture-Sets: *Pre-Heart Mountain Detachment*

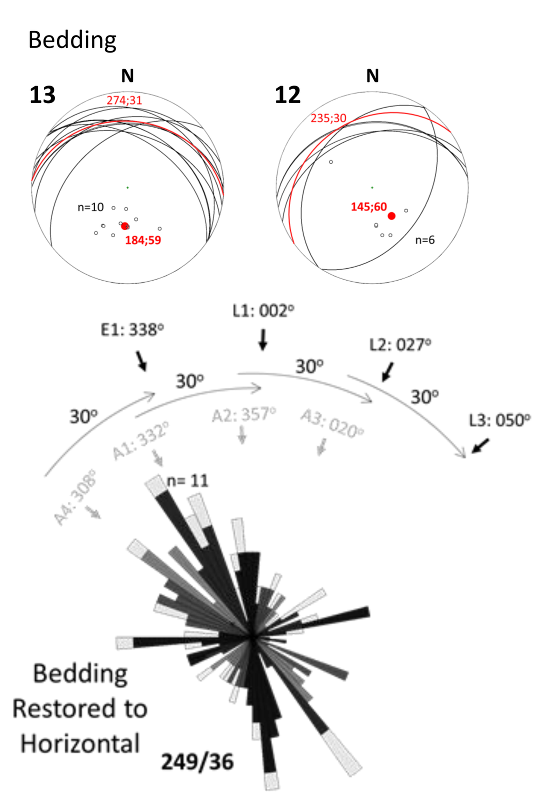
Sub-Detachment Fracture-Sets: *pinned to basement stratigraphy*

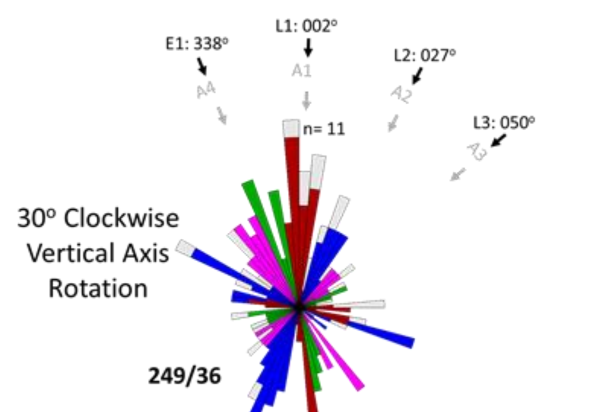
Fracture Sets within the Allochthon: *a small klippe on the western hill slope*

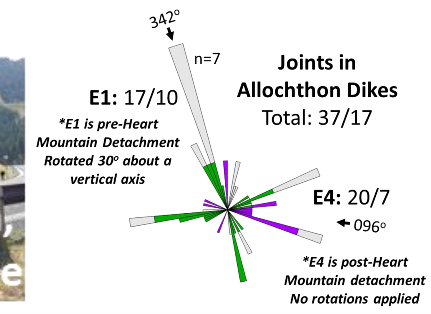




Allochthon Rotation

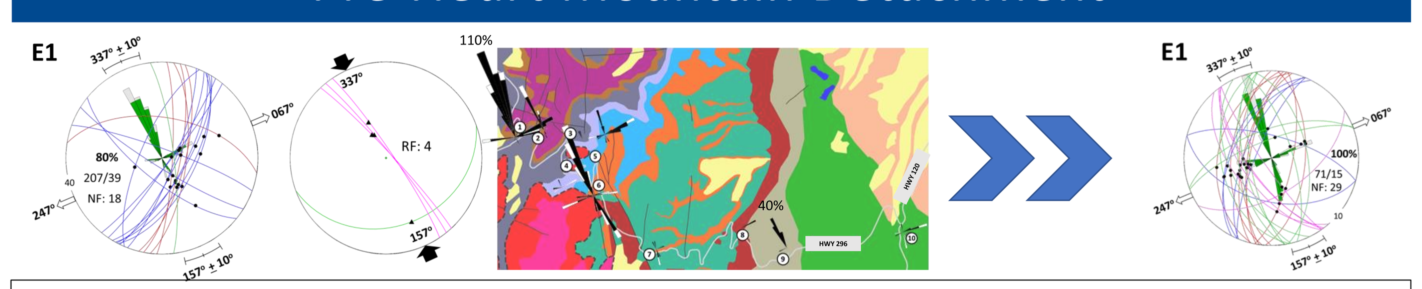






- After restoration of the allochthon's bedding to horizontal, the same Laramide and oldest Eocene fracture-framework of joint populations and age relationships are as were established for Laramide and oldest Eocene fractures pinned to basement below the detachment horizon
- Furthermore, the similarity of joint-orientation and the relative fracture-sequence can be used to determine how much rotation about a vertical axis occurred after as the detachment slid, relative to the pinned counterparts.
- The Madison Limestone and Bighorn Dolomite units in the allochthon road-cut show a clockwise rotation of ~30° to match the three bulk joint trends in pinned Dead Indian Hill strata.
- The detachment truncated Absaroka dikes which intrude the Paleozoic carbonates. The joints in the dikes constrain the Eocene fracture sequence, hence any joints in the Absaroka dike must be Eocene or younger.

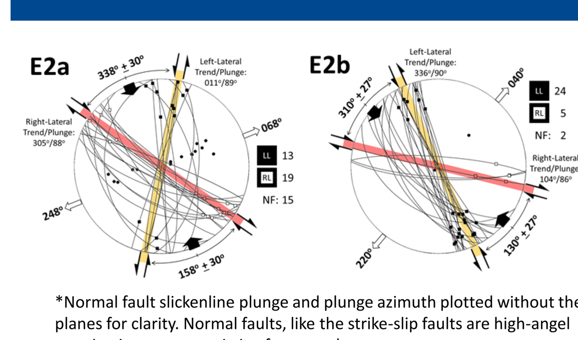
Dead Indian Hill: Eocene Fracture-Sets: *Pre-Heart Mountain Detachment*



(For all stereographic projections and rose diagrams)

- Rose diagrams and lower-hemisphere, equal-area, stereographic projection of the structural data (azimuth, 0°-360° following the Right-Hand-Rule) portray spatial representation, age relationships and overall number count of structural features.
- Open exterior arrows indicate the opening or extension directions of joints and faults (σ_3 or h_{min}).
- Black exterior arrows indicate the shortening direction and the mean azimuth of the fracture set (σ_1 or H_{max}).
- Numbers next to the rose diagrams note the normalized rose pedal size, the total number of joints over the number of joints which display age relationships, and the number of faults for each diagram.
- Rose diagrams are normalized to the exterior count label marked on the plots perimeter which remains consistent (*unless noted) for the fractures at each structural grouping ("Pinned" Dead Indian Hill, the allochthon, White Mountain, Heart Mountain).
- Rose pedal colors identify joints to a specific fracture-set, the grey rose pedals denote joints which had an abutting relationship (either younger or older) with an adjacent joint.
- Fault plane colors match the rose diagram colors to indicate the timing of the fracture formation and identify fracture reactivations in subsequent stress fields.
- The plunge and plunge azimuth of slickenlines on faults are plotted on the fault planes. Normal faults (NF) are marked as black dots, Reverse faults (RF) are marked as black triangles, Left-Lateral (LL) strike-slip faults are black squares and Right-Lateral (RL) strike-slip faults are hollow squares.

Eocene Fracture-Sets: *Heart Mountain Detachment in the Allochthon*



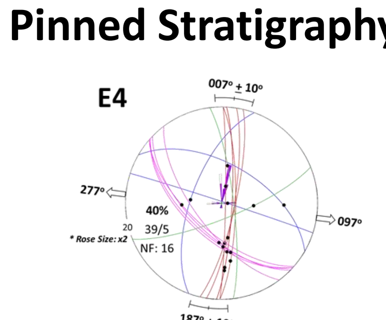
*Normal fault slickenline plunge and plunge azimuth plotted without the planes for clarity. Normal faults, like the strike-slip faults are high-angel reactivations on pre-existing fracture planes.

- The E1-fracture-set relates to the extension of the crust due to an Absaroka thermal bulge and weakening the domal surface.
- The ensuing fracture reactivations as strike-slip faults indicate a (southward) counterclockwise 28° rotation of the σ_1 orientation, defined by the line which bisects dihedral angle of the conjugate pairs.
- These strike-slip subsets likely happened in rapid succession as the northeastern slope of the Absaroka edifice failed (collapsed) following E1-extension.

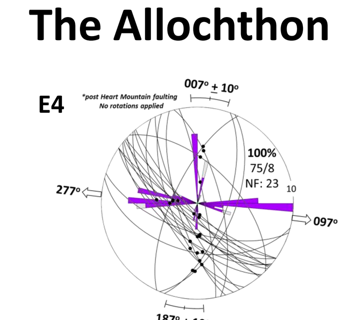
Eocene Fracture-Sets: *Post-Heart Mountain Detachment*

- The E-4 fracture-set is the youngest in the research area and developed after the detachment event.
- Orthogonal joints and high-angle fractures reactivated as normal faults (vertical σ_1) across the western hillslope of Dead Indian Hill shows the subsidence of the Sunlight Valley following the gravity-slide.

Pinned Stratigraphy



The Allochthon



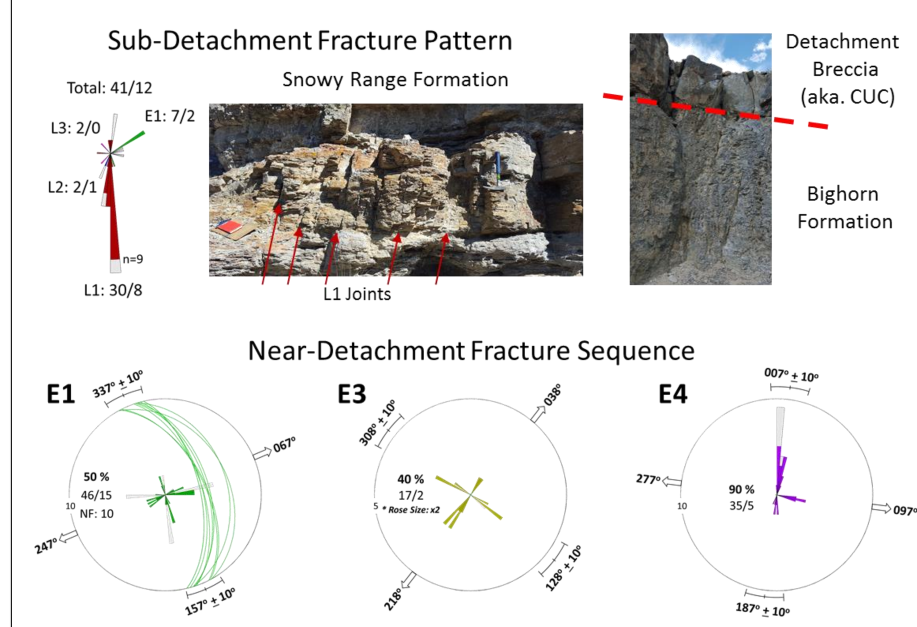
Regional Fracture-Set Continuity

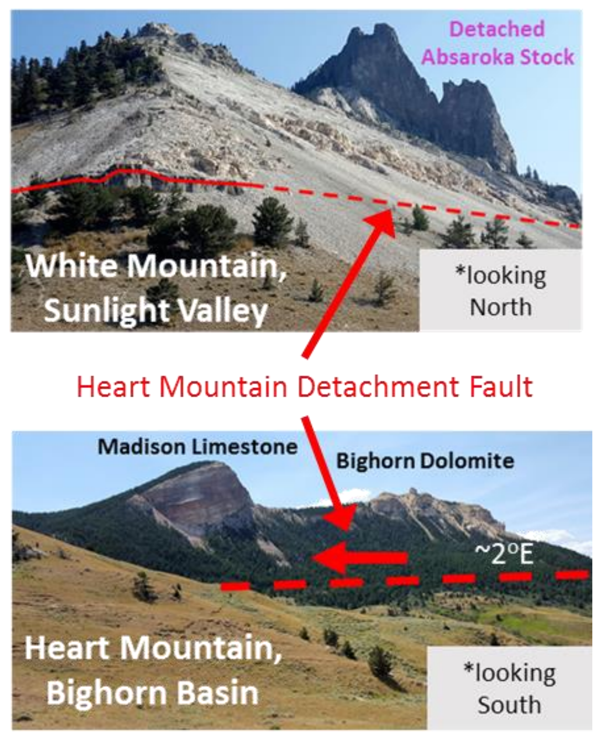
The angular and abutting relationships and joint populations of Laramide and Eocene fracture sequences in the pinned and allochthonous Dead Indian Hill strata are readily recognizable in the neighboring areas to the west (at White Mountain) and east (at the Heart Mountain klippe in the Bighorn Basin), including joints of the E3 fracture-set which is the resultant stress of the E2 strike-slip-set.

At White Mountain in the flat-lying Cambrian Snow Range Formation, the pre-detachment joint sequence is evident. Above in proximity to the detachment horizon, altered Bighorn Dolomite and a unique fault rock (Carbonate Ultracataclasite) at the display the Eocene joint progression.

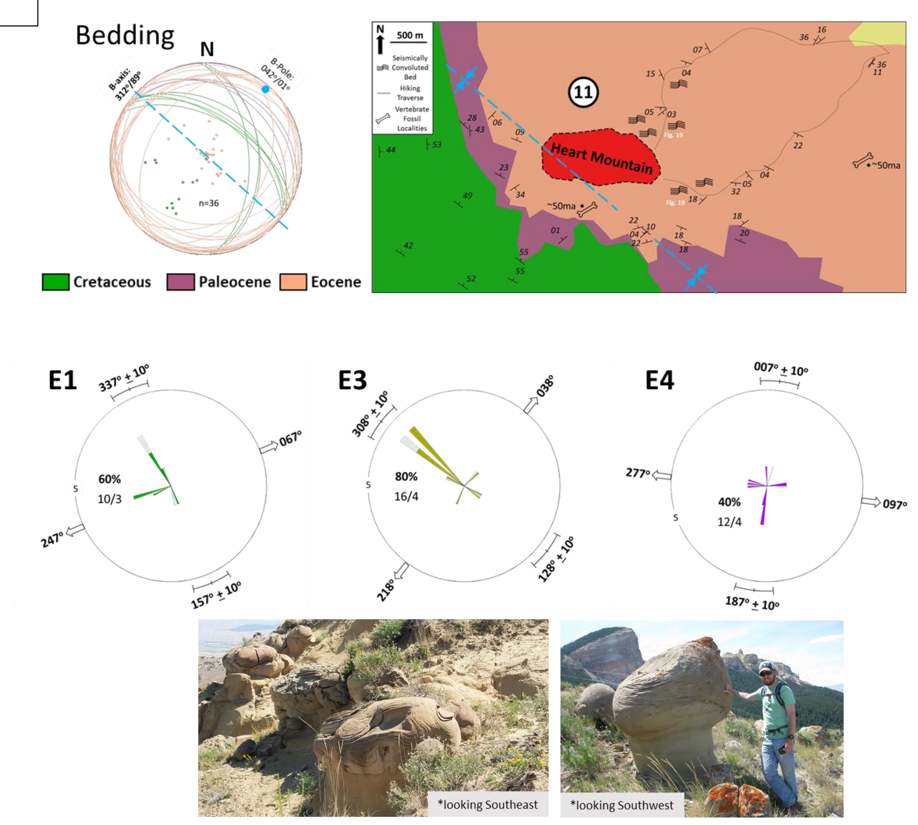
In addition to the Eocene fracture sequence in the Willwood Formation below Heart Mountain, multiple thick sandstone beds (> 2m) are highly convoluted and laterally extensive around the northern fringe of the mountain. These beds may be paleoseismites, which could likely reflect emplacement of the Heart Mountain klippe into the basin.

White Mountain Fracture-Sets

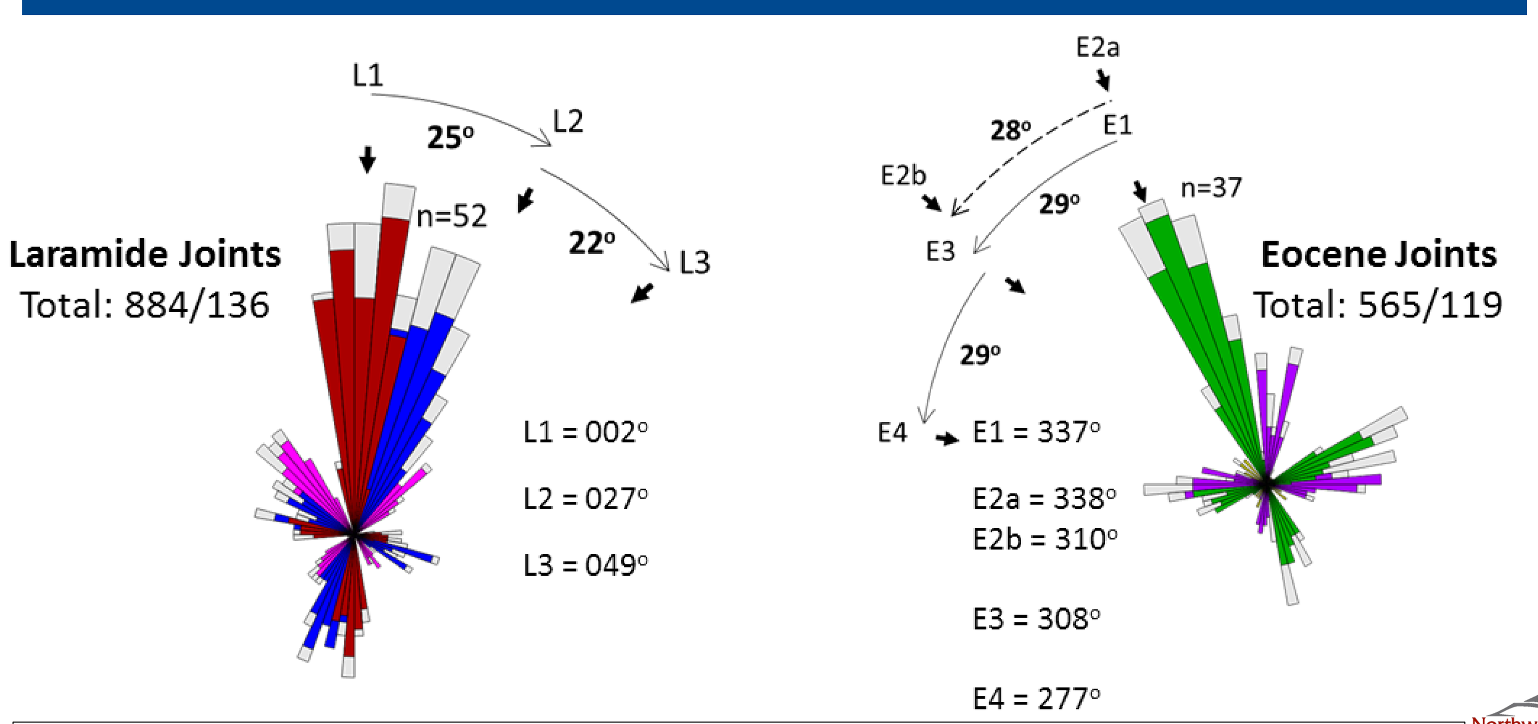




Willwood Formation Fracture-Sets



The Dead Indian Hill and the Heart Mountain Detachment Fracture Sequence



The meso-scale brittle fracture framework of joints and faults found within the Heart Mountain detachment and the underlying pinned stratigraphy is remarkably consistent. Based upon the abutting and angular relationships of joints, reactivation of pre-existing fractures as faults in subsequent stress fields and joint development in chronostratigraphic horizons we isolated the passive lead into the Laramide Orogeny (L1), the active orogenic compression of the Laramide Orogeny (L2 & L3), the thermal expansion of the crust brought on by the Absaroka Volcanic Province (E1), the rapid transport of the Heart Mountain detachment and collapse of the northeastern Absaroka edifice, along with continued post-detachment extension throughout the area. The angular relationship and gross population of the joint-sets lead to not just identification of Laramide and Eocene fracture patterns but also allowed us to quantify ~30° counter clockwise vertical axis rotation of the allochthon on the slope of Dead Indian Hill. The present relief of the "transgressive ramp" is a post-detachment feature cause by the failure of the northeastern Absaroka edifice and the thermal subsidence of Sunlight Valley as the Absaroka thermal bulge relaxed against the "pinned" Laramide platform.

Craddock, J. P., Malone, D. H., Magloughlin, J., Cook, A. L., Rieser, M. E., and Doyle, J. R., 2009, Dynamics of the 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, no. 5-6, p. 919-938.

Erslev, E. A., 1993, Thrusts, back-thrusts, and detachment of Rocky Mountain foreland arches: Special Paper - Geological Society of America, v. 280, p. 339-358.

Goren, L., Aharonov, E., and Anders, M. H., 2010, The long runout of the Heart Mountain landslide: Heating, pressurization, and carbonate decomposition: Journal of Geophysical Research-Solid Earth, v. 115.

Green, G. N., and Drouillard, P. H., 1994, The digital geologic map of Wyoming in ARC/INFO format: U. S. Geological Survey : Reston, VA, United States, vector digital data.

Hauge, T. A., 1985, Gravity-Spreading Origin of the Heart Mountain Allochthon, Northwestern Wyoming: Geological Society of America Bulletin, v. 96, no. 11, p. 1440-1456.

Pierce, W. G., 1973, Principal Features of the Heart Mountain Fault and the Mechanism Problem: United States, John Wiley & Sons, New York, p. 457-471.