Footwall deformation in the bedding-parallel portion of the Heart Mountain detachment, northwestern Wyoming

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INTRODUCTION

The Heart Mountain detachment is a low angle normal fault that crops out along the southwestern wall of the Clarks Fork Valley and as isolated klippen in the Bighorn Basin of northwestern Wyoming. The fault has been the subject of controversy since its discovery over 100 years ago, and continues to be one of the great puzzles of structural geology. The geometry and mechanism of movement of the Heart Mountain detachment have been extensively debated, but deformation in the footwall of the fault has received little more than brief mention in the literature. The purpose of this study is to characterize footwall deformation in the bedding-parallel portion of the detachment, and to compare footwall deformation to existing models for allochthon movement. A secondary goal of this study is to propose a reason for detachment formation in the Bighorn Dolomite rather than in Cambrian shales only a few meters below.

GEOLOGIC SETTING

The Heart Mountain detachment extends more that 80 km from the break-away fault near the northeast entrance to Yellowstone National Park to Heart Mountain and possibly McCulloch peaks in the Bighorn Basin (see area map, figure 3, Carson et al., this volume). In the Clarks Fork Valley the fault is confined to a bedding horizon in the Ordovician Bighorn Dolomite that slopes only 2° to the southeast. In the area of Dead Indian Hill the fault ramps, cutting up through the stratigraphy and then moving onto the former Eocene land surface in the Bighorn Basin. The allochthon, originally a few kilometers thick and 1300 km^2 in area, thinned during faulting to less than 1 km and spread out to cover an area of more than 3400 km^2. The allochthon moved to the southeast, and its leading edge traveled up to 50 km (Beutner and Craven, 1996). The hanging wall allochthon consists of Paleozoic carbonate rocks and Eocene Absaroka volcanics and is injected with numerous dikes and plutons. Footwall rocks in the bedding-parallel section of the fault are nearly flat lying Paleozoic carbonates and shales, and are relatively undeformed by faulting and are cut by few dikes.

Various models have been proposed for both the overall geometry and mechanism of movement of the Heart Mountain detachment. Reviews of these models are presented in Pierce (1973) and Hauge (1993). A more recent model (Beutner and Craven, 1996) is directly relevant to my research and findings. According to this model, a layer of volcanic gas was injected along a bedding plane in the Bighorn dolomite. This fluidized material was able to buoy the rocks above it, reducing friction to zero across the bedding horizon. Because the hanging wall rocks were on a slight slope, they began to slide by gravity. As the hanging wall moved, it thinned through normal faulting. Eventually gasses along the fault plane escaped through vents or along hanging wall faults, and the allochthon came back into contact with the footwall. Faulting, according to this model, proceeded at catastrophic rates. Evidence for this model includes a string of plutons between White Mountain and Hurricane Mesa that Beutner and Craven (1996) interpreted as analogous to a hot spot trace: as the allochthon moved over a stationary volcanic neck below Hurricane Mesa, magma injected regularly into the hanging wall. Further, Beutner and Craven (1996) reported the presence of accreted grains similar to accretionary lapilli, and delicate, intact shards of volcanic glass in microbreccia along the fault plane. As usual faulting processes would quickly destroy such delicate grains, Beutner and Craven (1996) argued that the most probable source of these intact grains would have been an injection of primary volcanic material and gasses. Models for an injection of gas or steam along the fault plane have earlier been proposed by Voight (1974), Hughes (1970), and Prostka (1978), but the model of Beutner and Craven (1996) is the most comprehensive of these models, and fits best with the characteristics of footwall deformation.

RESULTS

Deformation in the bedding-parallel portion of the Heart Mountain detachment footwall is remarkably limited: the fault crops out along much of 50 km of the Clarks Fork Valley, yet only at three or possibly four locations is deformation extensive. Near vertical fractures are common in the footwall of the detachment, but fracture density is extremely variable. In some places fractures are only 5 cm apart while in others they are spaced up to one meter or more apart. Fractures are consistent in density and orientation at least to the base of the Bighorn Dolomite. To determine whether fractures in the footwall are the result of regional joint set formation or of faulting,

Bighorn Mtn.	**Mid. Rockies;**	**Beartooth Mtn**	**Clarks Fork**
(Hudson, 1969)	[Microjoints]	(Spencer, 1959)	
	(Wise, 1964)		
N 10-17° E	N 10° E	N 0-10° E	N 10° E
N 21-44° E	N 25° E	N 15-25° E	N 15-25° E
-	N 85° E	N 85-90° E	N 80-90° E
N 70-88° W	N 70° W	N 60-70° W	N 60-70° W*
N 37-47° W	N 45° W	N 45° W	N 40-50° W*
-	N 65° E	N 60° E	N 40-60° E *
-	N 10° W	N 15-20° W	N 15-30° W
N 45-58° E	N 45° E	N 45° E	-
* Prominent Trend in Northern Lineaments			

Table II. Prominent fracture and microfracture trends for the Bighorn Mountains, Middle Rocky Mountains, Beartooth Mountains, and Clarks Fork Valley.

SUMMARY AND CONCLUSIONS

It is difficult to discern with certainty the origin and relative ages of the fracture patterns seen in Clarks Fork Valley, due to the high complexity of fracturing, a general absence of datable dikes and mineralization, and a relative absence of stress indicators. However, based on field evidence and comparisons with work done in surrounding areas, some inferences can be made concerning the tectonic history of Clarks Fork Valley. The fracture patterns found in the Clarks Fork Valley suggest at least two major phases of deformation, Precambrian and Laramide. The pronounced development of N 10-30° E trending fractures noted in ground measurements and photo lineaments, coupled with their prevalence in the overlying sedimentary units, and prominence in surrounding Precambrian basement ranges, suggests that these fractures represent a regional Precambrian deformation event. In several locations, this initial trend is offset by prominent EW trending fractures.

Lee and Wise (1983) described two phases of Laramide deformation for the area: a main NE-SW horizontal compression followed by a later phase of WNW-ESE compression. In the Clarks Fork Valley the angle between major faults is consistent with the angle between major fracture sets, suggesting that the faults and fractures were created within the same stress field and the faults possibly formed along the pre-existing fractures. The main phase of Laramide NE compression could account for the prominent NW trending fractures found throughout the valley in both the basement and sedimentary units and seems responsible for the major fault zones, principally along the valley and in the Sunlight Creek Basin. A possible second phase of Laramide deformation involving WNW-ESE compression was partly controlled by the established Precambrian zones of weakness, reactivating many N 10-20° E trending faults and fractures.

REFERENCES CITED

Hudson, Robert, 1969, Structural Geology of the Piney Creek Thrust Area Bighorn Mountains, Wyoming: Geol. Soc. America Bull., v.80 pp. 283-296

Lee, Allison M., and Wise, Donald U., 1983, Evidence For Late Laramide WNW Compression In the Northern Wyoming Province: Abstracts with Programs, Geol. Soc. America, v.15, no. 6, p.514

Pierce, W. G., 1965, Geologic map of the Deep Lake quadrangle, Park County, Wyoming: U.S. Geol. Survey Map GQ-478, scale 1:62,500

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

---------., 1971, Geologic map of the Beartooth Butte quadrangle, Park County, Wyoming: U.S. Geol. Survey Map GQ-935, scale 1:62,500

Spencer, Edgar W., 1959, Geologic Evolution of the Beartooth Mountains, Montana and Wyoming, Part 2: Fracture Patterns: Geol. Soc. America Bull., v.70, pp.467-508

Wise, Donald U., 1964, Microjointing in Basement, Middle Rocky Mountains of Montana and Wyoming: Geol. Soc. America Bull., v.75, pp.287-306

----------., 1982, A New Method of Fracture Analysis: Azimuth Versus Traverse Distance Plots: Geol. Soc. America Bull., v.93, pp.889-897

I obtained data for the regional joint set from Ashley LaForge (see her paper this volume). I determined the dominant fracture orientation indicated by her data set for the Pilgrim Limestone, and then subtracted all fracture sets striking in this direction from my data set for footwall fractures. The result is shown in figure 1. There is some scatter in fracture orientation, but fractures dominantly strike between 30 and 70° and 210 and 240. Footwall fractures therefore strike close to perpendicular to 120°, the direction of allochthon movement. This is an expected orientation for brittle fractures related to faulting (Twiss and Moores, 1992, p. 61-62).

Footwall faults also align with the direction of faulting. Figure 2 is a stereonet plot of all faults and lineations recorded in the footwall. Most faults strike close to perpendicular to 120°, the direction of allochthon movement, and lineations trend in this direction as well. Again, minor faults in this orientation are what would be expected based on the direction of faulting. Lineations on fault planes are always grooves or scratches, and never mineral growth slickenlines. Though this does not prove faulting was fast, it gives no evidence that faulting was slow. Further, footwall faults are rarely injected with microbreccia, and in fact, microbreccia injections are only present in anomalous areas along the fault. This suggests that most footwall faulting occurred after gasses had been released, when there was not enough pressure in the fault plane to forcibly inject material into the footwall. Minor footwall faults probably formed after volcanic gasses along the fault plane had escaped and hanging wall blocks came back into contact with the footwall at a late stage in the faulting event.

Figure 1

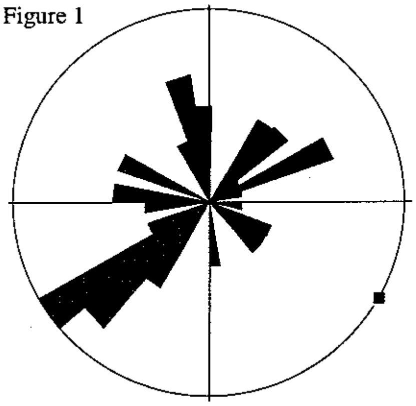

Figure 2

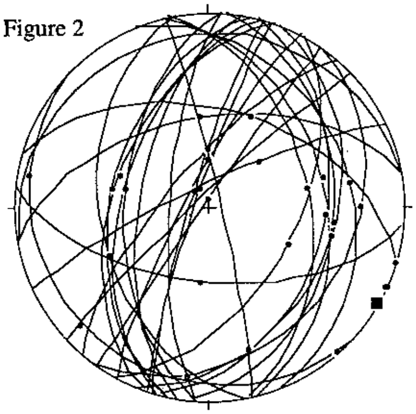

Figure 1. Total orientation and distribution of foot wall fractures with regional joint set data subtracted. Fracture orientation is plotted on an 11% rose diagram on Almendinger Stereonet v.4.9.6. Square plotted at 120 degrees indicates direction of allochthon movement.

Figure 2. Orientation of foot wall faults. Faults are plotted as great circles with lineations, when present, indicated by a point. Square plotted at 120 degrees indicates direction of allochthon movement. Faults are plotted using Almendinger Stereonet v.4.9.6.

In a few locations I observed fanning fractures in the footwall. These fractures strike parallel to each other and "fan out" from a single, often brecciated, point along the Heart Mountain detachment fault plane itself or from a minor, parallel, footwall fault. Dips are all in the same direction, towards 120°, and vary from 0° to 90°. Footwall rocks in the area of fanning structures are often brecciated. I interpret these structures as the result of a rough spot along a fault where hanging wall and footwall rocks caught against each other. Footwall rocks reacted to this by shattering, brecciating, and forming fractures that originated from the point of loading. Such behavior could be caused by catastrophic rates of faulting, but slower faulting rates could also produce these structures.

As described above, deformation is minimal almost everywhere below the fault plane. However, there are a few locations of anomalous fault behavior. At both Jim Smith Creek and Onemile/Squaw Creek, the fault does not follow the usual detachment horizon in the Bighorn Dolomite, but rather cuts into the Snowy Range Formation of the footwall. The fault is remarkably planar in these locations. One way to explain this is by the presence of fluidized material along the fault plane: just as dikes and sills propagate their own planar fractures, fluidized volcanic gasses might propagate their own planar fault, especially where there is a slight structural arch in footwall rocks. Further, footwall rocks in these anomalous sites are frequently faulted, brecciated and deformed, and microbreccia is locally injected into the footwall. At these sites, in contrast to deformation along the majority of the fault plane, deformation apparently occurred while microbreccia was still fluidized and pressurized in the fault plane.

The Crandall Conglomerate is an Eocene unit deposited both above and below the Heart Mountain detachment in what was probably a deep river canyon (Pierce and Nelson, 1973). Where the detachment cuts through the Crandall Conglomerate, extensive fracturing occurs, with cobbles of the conglomerate fractured at least 5 m below the fault plane. Multiple, parallel fractures occur within each cobble, with offsets of approximately 1 mm along each fracture. Fracture planes vary somewhat in orientation from cobble to cobble, but when measured and plotted, all give a general orientation striking close to perpendicular to the direction of allochthon movement with dips to the Southeast (see figure 3). Cobbles directly at the fault plane are sheared, leaving a completely planar fault surface.

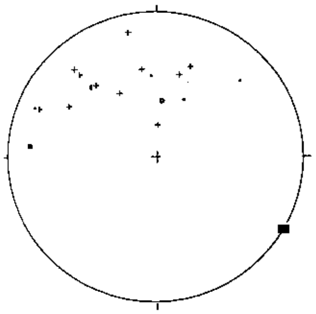

Figure 3. Stereographic distribution of fracture planes in the Crandall Conglomerate using Almendinger Stereonet v. 4.9.6. Plotted points are poles to fracture planes. Square plotted at 120 degrees indicates direction of allochthon movement. Offsets are according to legend below.

- \+ normal offset
- ★ reverse offset
- ● unknown offset

DISCUSSION

Evaluation of models. My research and observations of the Heart Mountain detachment footwall are most consistent with a model of brittle, catastrophic faulting and the presence of fluidized material along the fault plane. The model of Beutner and Craven (1996) is the most complete and fits best with all currently available data about the Heart Mountain detachment. Faults and fractures in the footwall are clearly the result of brittle deformation, and of allochthon movement towards 120°. Fanning fractures in the footwall and accompanying breccia are the likely result of rough spots along the detachment horizon where hanging wall blocks caught against the footwall. Though this does not prove catastrophic faulting, it is consistent with it. Strong support for a catastrophic mode of faulting comes from a study of footwall calcite twins by Neilson et al. (1996). Movement of the Heart Mountain detachment has not overprinted calcite strain twins in the footwall, and therefore, as the formation of calcite twins is a time dependent process, faulting must have occurred at a catastrophic rate.

The results of this study support the presence of fluidized material along the fault plane. The extremely planar propagation of the fault in anomalous areas can be explained by the presence of fluidized material in the fault plane. The most convincing argument, however, for an injection of volcanic gas along the fault plane is the surprisingly small amount of deformation in the footwall. Considering that up to 4 km of overlying rock moved as much as 50 km along the footwall, the lack of deformation is incredible. A layer of volcanic gas along the fault plane would cushion the footwall until hanging wall blocks had nearly completed their motion, thus protecting the footwall from almost all deformation. Further, my research indicates that most footwall deformation occurred after fluid pressure had decreased in the fault plane, as microbreccia is seldom seen injected into footwall structures. Deformation in the footwall would not occur until volcanic gasses had leaked from the fault plane and hanging wall block came back into contact with the footwall.

Fault placement. If the mechanism of fault movement is adequately explained by the volcanic fluidization model of Beutner and Craven (1996), then the only major remaining question is why the Heart Mountain detachment formed in a bedding horizon of the Bighorn Dolomite rather than forming in a weaker shale unit just a few meters below. This is bizarre behavior for such a low angle fault. In my own field work, I have observed that the bedding horizon is fault prone in regions outside the bedding-parallel portion of the Heart Mountain detachment, suggesting that this particular horizon is a likely place for a major detachment fault to form. The work of Stearns et al. (1974) elaborates and supports these observations.

A further explanation for fault placement is based on an application of the mechanics of sill injection, as proposed in Gretener (1969), to the Heart Mountain detachment. Gretener (1969) argues that the intrusion of sills depends on the stresses placed on a region. Assuming that σz is vertical, lithostatic stress, that σx and σy are horizontal, and that force is applied in the x direction, then sill intrusion occurs at or near the base of regions where σx is greater than σy, and σy is greater than σz (see figure 4). The strongest mechanical and lithologic units, such as dolomites, are the most likely to meet these criterion. Therefore, it is at the base of strong units where sill injection occurs (Gretener, 1969). My argument is that the injection of gas along what was to become the fault plane would follow the same rules as sill injection. This argument requires that stresses in the Clarks Fork region were aligned vertically and horizontally, and that σx was in the horizontal direction, possibly related to Laramide age deformation, and that sill injection and the injection of volcanic gas are mechanically analagous. The occurrence of the detachment horizon fits this model perfectly: it is above a lithologically weak unit, the Snowy Range Formation, and at the base of a lithologically strong unit, the Bighorn Dolomite. Thus, assuming that the volcanic fluidization model is correct, then the most likely location for an injection of fluidized material is exactly where the Heart Mountain detachment occurs.

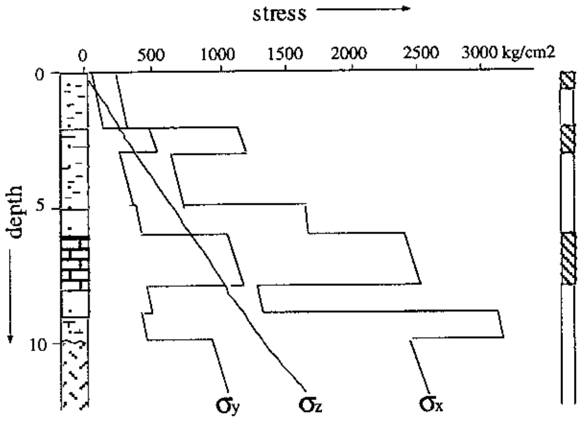

Figure 4. State of stress in the basement and sedimentary sequence. σz is vertical stress, and σx and σy are horizontal with compression in the σx direction. Stress varies with lithologic unit. When σx is greater than σy is greater than σz, then sill injection can occur. From Gretener (1969).

CONCLUSION

The purpose of this project was to collect for the first time a description of footwall deformation in the bedding-parallel portion of the Heart Mountain detachment. My study supports a model for catastrophic faulting, provides evidence against a slow-faulting mode, and indicates the presence of fluidized material along the fault plane. Therefore, observed footwall deformation most strongly supports the volcanic fluidization model of Beutner and Craven (1996). The model for sill injection of Gretener (1969) provides an explanation for the occurrence of the detachment along a bedding plane of the Bighorn dolomite rather than Cambrian shales below. A combination of the volcanic fluidization model (Beutner and Craven, 1996) and the model for sill injection (Gretener, 1969), provides the most comprehensive model yet for the formation and movement of the Heart Mountain fault.

REFERENCES CITED

Beutner, E.C., and Craven, A. E., 1996, Volcanic fluidization and the Heart Mountain detachment, Wyoming: Geology, v. 7, p. 595-598.

Gretener, P.E., 1969, On the mechanics of the intrusion of sills: Canadian Journal of Earth Sciences, v. 6, p. 1,415-1419.

Hauge, T.A., 1993, The Heart Mountain detachment, northwestern Wyoming: 100 years of controversy, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M, eds., Geology of Wyoming, Volume 2, Memoir No 5: Pioneer Printing and Stationary Company, Cheyenne, Wyoming, p. 530-571.

Hughes, C.J., 1970, The Heart Mountain detachment fault-- A volcanic phenomenon?: Journal of Geology, v. 78, p. 107-116.

Neilson, K.J., Craddock, J.P., and Malone, D.H., 1996, Calcite Twinning strains and the Heart Mountain detachment: tracking upper plate slide block kinematic motions and an absence of detachment-related strain overprints: Geological Society of America Abstracts with Programs, v. 28, p. 246.

Pierce, W.G., 1973, Principal Features of the Heart Mountain Fault and the Mechanism Problem *in* DeJong, K.A., Gravity and Tectonics: New York, John Wiley and Sons, p. 457-471.

Pierce, W.G., and Nelson, W.H., 1973, Crandall Conglomerate, and unusual stream deposit, and its relation to Heart Mountain faulting: Geological Society of America Bulletin, v. 84, p. 2631-2644.

Prostka, H.J., 1978, Heart Mountain fault and Absaroka volcanism, Wyoming and Montana, U.S.A. *in* Voight, B., ed., Rockslides and Avalanches 1: Natural Phenomena: New York, Elsevier North-Holland, Inc., p. 423-437.

Stearns, D. W., Logan, J. M., and Friedman, M., 1974, Structure of Rattlesnake Mountain and related rock mechanics investigations, *in* Voight, B., ed. Rock Mechanics, the American Northwest: 3rd Congress International Society of Rock Mechanics Expedition Guidebook: Special Publication, Experiment Station. College of Earth and Mineral Sciences, The Pennsylvania State University, p. 18-25.

Twiss, R.J., and Moores, E.M., 1992, Structural Geology: New York, W.H. Freeman and Company.

Voight, B., 1974, Roadlog: Wapiti- Heart Mountain- Canyon, *in* Voight, B., ed. Rock Mechanics, the American Northwest: 3rd Congress International Society of Rock Mechanics Expedition Guidebook: Special Publication, Experiment Station. College of Earth and Mineral Sciences, The Pennsylvania State University, p. 112-124.

The breccia layer of the Heart Mountain fault and related clastic dikes

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Introduction

The Heart Mountain allochthon moved along the nearly horizontal Heart Mountain fault as a continuously extending upper plate driven by the gravitational collapse of an unstable volcanic pile (Hauge, 1993). The allochthon is composed of carbonate and volcanic rock. Beutner and Craven (1996) studied the fault at White Mountain and proposed that the upper plate was buoyed up by a lateral injection of volcanic fluid from a volcanic center at Hurricane Mesa. A breccia layer exists along much of the fault and varies in thickness from 0-2 m. In numerous places this breccia was injected upward into the upper plate as clastic dikes. This study characterizes the breccia layer and clastic dikes along the length of the fault and try examines evidence for the cause of friction reduction along the fault plane.

Petrography

The breccia layer and clastic dikes are similar in composition and texture and are composed of a very fine grained (3-20 μm) carbonate matrix with mm and larger clasts of carbonate and volcanic rocks. Carbonate clasts are subangular to subrounded and are derived from the dolomites and limestones on both sides of the Heart Mountain fault. Volcanic clasts fall into three categories: 1) broken or unbroken single crystals, usually plagioclase, but occasionally amphibole and pyroxene; 2) yellow glass, with or without plagioclase and pyroxene microphenocrysts; 3) volcanic rock fragments, which are rare and found only in a few samples. Many volcanic clasts have been partially to nearly completely altered to calcite.

Clasts make up about 40% of the breccia; the rest is a matrix of fine grained carbonate with minor amounts of fine volcanic material and some clays. The breccia is usually massive but occasionally shows slight horizontal banding parallel to the fault. Imbrication is not present. The breccia sometimes armors clasts.

In one location, clasts of a distinct, earlier breccia are found within the breccia matrix. At least one of these breccia clasts contains a fragment of potassium feldspar. The presence of two distinct microbreccias suggests that there were at least two phases of faulting and that enough time elapsed between the two for the first breccia to lithify.

"Glass" clasts contain a yellow to opaque brown matrix of partially to completely devitrified volcanic glass, and commonly contain >50% plagioclase and pyroxene crystals. The shapes of the glass fragments vary considerably from rounded and equant to shards which are flattened parallel to the Heart Mountain fault. In some samples the glass has partially engulfed carbonate clasts.

The proportion of both volcanic and glass clasts decreases with distance from Hurricane Mesa, a known volcanic center (figure 1).

Volcanic glass compositions

The compositions of the glass fragments vary considerably (figure 2). When compared to the Wapiti volcanics and the allochthonous plutons in the upper plate of the Heart Mountain fault (see Stone, this volume) the glass compositions are typically higher in SiO_2, Na_2O, K_2O, and lower in CaO, Al_2O_3, and MgO. Some of this variation may be the result of devitrification or metasomatic alteration of the glass. However, even the analyses of the least altered glass do not match the analyses of surrounding igneous rocks. The chemical analyses of the Wapiti formation and the plutons are whole-rock analyses, including crystallized components that came up with the magma. The glass analyses represent compositions of the *interstitial magma* between those phenocrysts. By adding the compositions of possible phenocrysts to the glass we can create glass plus crystal compositions similar to those of the other igneous rocks.