Deformation and possible thermal signatures in the footwall of the Heart Mountain detachment: Wyoming - Montana

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INTRODUCTION

The Heart Mountain detachment ranks among the most studied and most enigmatic structures in North America. Since the discovery of the Heart Mountain klippe, the fault has been described and explained as everything from a cylindrical fault to a giant rock glacier. In its entirety, the detachment covers 3000 km^2 , and spans 100 km from Silver Gate, Montana to McCullough peak in Wyoming. The morphology of the detachment involves a combination of four general types of faults. The Abiathar break-away fault near Silver Gate, Montana is the first expression of the detachment. After the break-away, the bedding-parallel portion of the fault begins and continues to Dead Indian Hill Here begins the ramp portion, where the fault cuts across bedding and ascends in elevation until it again levels and follows what W.D. Pierce (1973) calls the former land surface. See Hauge (1993); Pierce (1973); and Beutner and Craven (1996), for reviews of theories of motion.

Autochthonous rocks of the detachment consist of two main types: 1) the Cambrian Snowy Range Formation (Csr), a minor cliff-former (<6 m) and relatively competent shale with interbedded flat-pebble conglomerate; and 2) the basal beds (≈2 m) of the Ordovician Bighorn Dolomite (Obd), a mottled thrombolitic dolomite varying from light tan to dark grey. A third rock type, the Crandall Conglomerate, is an intrabasinal clast-supported conglomerate that crops out locally and is cut by the detachment. The footwall of the detachment locally also contains igneous and clastic dikes.

Allochthonous rocks of the detachment consist of boulder- to mountain-sized masses of the following rock types: 1) Tertiary Absaroka Volcanics, which consist of volcanics, volcaniclastics, breccias, and sandstones derived from volcanic sources; 2) the Mississippian Madison Limestone, a crystalline grey limestone with yellow tones; 3) the Devonian Jefferson - Three Forks Formation, chocolate-brown carbonate rocks that give off a strong diesel smell when fresh pieces are broken; 4) the Crandall Conglomerate, an intrabasinal clast-supported conglomerate; and 5) igneous plutons that are often cut by several generations of dikes.

At various localities along the fault plane, a layer of microbreccia has been identified that consist of volcanic glass, carbonate clasts, and volcanic clasts. Where this layer exists, it varies in thickness from greater than two metres to a millimetre-scale veneer. The microbreccia layer is locally injected into both the hangingwall and the footwall.

My project furthers a systematic study of the footwall at the outcrop and microscopic scales to determine the extent and cause of deformation. Analysis of clays in the footwall rocks was used to determine whether upper-plate plutons were hot at the time of their arrival. The results are used to evaluate the volcanic fluidization theory of faulting.

METHODS

I examined fault exposures for signs of deformation by looking for features such as fracture sets, clastic dikes, brecciation, secondary detachments, cataclasis, microbreccia, pressure solution, slickensides, mineral growth, metamorphism, recrystallization, and any structures that indicated direction of movement. All samples taken of the footwall were oriented. Field work for the clay analysis consisted of collecting a series of samples close to the fault plane and as far below the fault as practical to determine the range of clay alteration. Blanks of the oriented samples were cut parallel to S. 30° E., the direction of fault motion

Procedures for dissolving carbonate from the samples, separating the <2 μm fraction, and preparing slides for X-ray diffraction followed Moore and Reynolds (1989). I prepared XRD clay slides in small batches, starting with samples farthest from the fault plane. Eight replicate samples were prepared and run in order to calculate standard deviations. I X-rayed samples with a Siemens diffractometer with Cu-radiation from 3 to 16 degrees 2θ with settings 35 Kv and 22 mA. Data were collected by a Dapples system, and I later identified and analyzed peaks using the program MacDiff, which includes an 8000 sample mineral database skewed towards clay minerals.

RESULTS

Clay Analysis. One of the purposes of this project was to determine whether detrital clays contained in footwall carbonates beneath hangingwall plutons underwent post-diagenetic metamorphism. Visibly, except for White Mountain, there are no signs of metamorphism in any Heart Mountain detachment (HMD) exposures beneath the three plutons sampled in this study. Signs of metamorphism in the footwall, no matter how low-grade, are very important to understanding the timing of motion on the HMD and the history of pluton injection in the area. According to the volcanic fluidization theory (Beutner and Craven, 1996), plutons were injected contemporaneously with faulting with the White Mountain pluton coming in before major Heart Mountain faulting began. This theory also calls for catastrophic faulting, with the majority of the motion being complete on the scale of hours (Beutner and Craven, 1996). In this case, it would be expected that the footwall would show signs of metamorphism due to heating from the upper-plate plutons. According to the expanding allochthon theory, which employs a mechanism for slow faulting, on the scale of millions of years (Hauge, 1993), there would be enough time for the upper-plate plutons to cool before reaching their present positions and not have significantly affected the lower plate. A third possibility is that there was a fast faulting mechanism, but the upper-plate plutons were already cool and were simply moved along with the allochthon. This possibility removes synmovement pluton emplacement as source for a fluidized layer lessening friction along the fault plane.

Many clays show marked changes in various properties when they undergo post-diagenetic heating. This type of analysis of very low grade metamorphism (VLGM) is used by oil companies to determine the history of heating and fluid movement in oil-bearing basins, and by metamorphic petrologists to characterize the boundaries of metamorphic facies. The rocks from the footwall of the HMD below upper-plate plutons contain saponite, a smectite, which upon heating undergoes 2 reactions that can be evidenced by X-ray diffraction (Deer, et al., 1962). At 100°C and at 500°C the d-spacing of saponite shifts from ≈14 Å to 10Å and to 9.6 - 10 Å, respectively. This shift in basal d-spacing occurs because of the systematic expulsion of OH^- groups from the clay structure. This process is reversible up to the point where metamorphism causes the clay's lattice to change size.

In my study I was able to X-ray samples from the fault plane extending to about one metre below the HMD I was unable to prepare slides below this level because the rock type changed from dolomite (from which I separated detrital clays) to shale. The shale did not dissolve or disaggregate in the solution that I used for the dolomites, but the acid did leach ions from the shales (coloring the acid solution orange). Also, the dolomites were easily broken to the proper size in a rock crusher, whereas the clay-rich rocks split into thinner, but not smaller, pieces which fell through the crusher still in pieces too large to have enough surface area to dissolve. A third consideration was that the dolomites have only one type of clay, whereas the shales, having had a different environment and source area, likely have several different types of clays, which would make the comparison of the two very difficult.

I was able to graph and compare d-spacing, full-width at half-maximum (FWHM), and peak broadness of my samples with confidence because of a set of replicates. If the clays had been heated it would be expected that the d-spacing would be smaller closer to the fault plane. Site 6 does exhibit this trend, but it does not hold for the other two sample sites. FWHM is a measure of "crystallinity", an index of how well crystallized the clay is, and is used in determining the amount of heating in illites. In my samples, FWHM plots as a straight line for the best peak at each of the sites. Site 6 showed no trend in broadness, and sites 5 and 7 showed a very weak trend with increasing broadness with depth. The lack of trends in the samples suggest that there was not enough heating from the upper plate to overprint the diagenetic clay structures.

Field and Structural Analysis. Field work in the summer of 1997 entailed a continuation of the study of footwall deformation begun by L. Schoenbohm in 1996. Although there is little apparent deformation in many areas where the Heart Mountain detachment is exposed, further examination of outcrops shows that the deformation zone is much more extensive than previously described.

Fractures perpendicular to the fault plane are common. Schoenbohm (1997) showed that a fracture set dipping toward 120° is unrelated to the regional joint system, and is related to brittle deformation along the fault plane. Several of HMD exposures in Sunlight Valley are characterized by a strong, nearly vertical N. 30° E. fracture set (see Fig. 1), and other nearby exposures have S. 10° E. fractures that are also nearly vertical. The N. 30° E. fracture set is nearly orthogonal to the direction of motion, and is not overprinted or overprinting other fracture patterns. Outcrops having this distinct fracture pattern did not exhibit other forms of deformation.

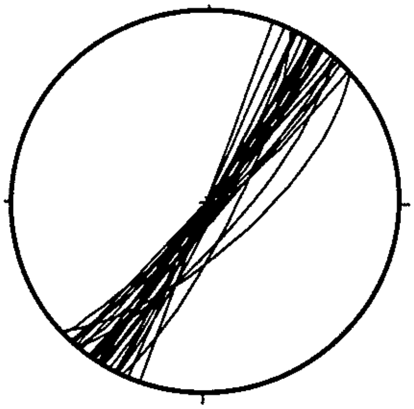

Figure 1

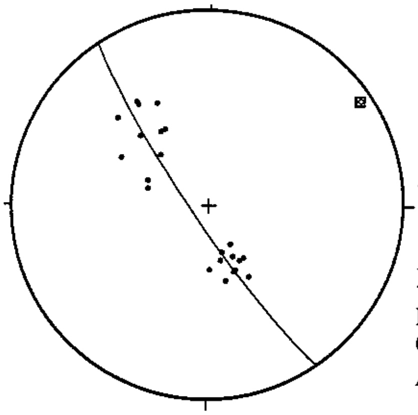

Figure 2

Figure 1. Fracture orientations from outcrops near Spring Creek in Sunlight Valley. Plotted on Allmendinger Stereonet 4.9.

Figure 2. Bedding planes plotted as poles of a footwall fold at Squaw Creek. Plunge is 7°. Plotted on Allmendinger Stereonet 4.9.

Another characteristic of brittle deformation found in Sunlight Valley is that there are local, minor secondary detachments. These detachments occurred at about the same place in the footwall at three sites, along parting planes, although they did vary in vertical position along the outcrops. The strongest secondary detachment varied in location from the Csr-Obh boundary to 30 cm higher. Sheared material was found along the detachment surface, and at one location there were several clasts of carbonate breccia in the sheared material. Another secondary detachment occurs between 30 and 50 cm above the first. There is no evidence that either of these detachments accommodated more than cm scale motion, and there was also no evidence of ductile deformation associated with either secondary detachment. This suggests that detachments propagated quickly utilizing weak points in the footwall rather than deforming ductily. A second line of evidence for the fast propagation of the secondary detachments is that at one location a fanning fracture, first described by Schoenbohm (1997), was associated with the secondary detachment. The fracture's origin was along a small ramp in a secondary detachment that was being employed to accept displacement from a small footwall graben. When the detachment reached an irregularity along the parting plane that it was utilizing, it set up a secondary stress field. This caused the fractures, and the secondary detachment cut across bedding to a weaker plane. The fact that footwall stress was accommodated by brittle deformation enforces the idea that faulting was too fast for ductile processes.

At the majority of the HMD exposures megascopic deformation is restricted to brecciation and fracturing; however, at several sites deformation is much more intense. One of these locations is at Squaw Creek where the HMD crosses a limb of the Blacktail anticline. Here the fault is much lower in the stratigraphic section than at any other location, possibly lower than the Grove Creek Member of the Snowy Range Formation. Footwall rocks consist of highly sheared green to black shales, with a crude near-vertical foliation that slightly bends around floating single pebbles of highly fractured and rehealed flat-pebble conglomerate. Slickenlines on the footwall about 30 cm below the detachment are oriented at S. 60° E., and horizontal extensional boudins are oriented normal to these slicks at N. 20° E. This outcrop also contains a footwall anticline with a wavelength of ≈10 metres in crystalline limestone with small flat pebbles and fossil fragments (see Fig. 2) about 5 m below the HMD. The fold trends about N. 50 E. with a 7° SW. plunge. Bedding within the fold has remained planar, with curvature caused by internal brecciation. Though this outcrop contains an anomalously high amount of deformation, none of it is ductile. The severity of deformation in this area may be a result of a stress build-up as the fault was forced to propagate through the very competent Crandall Conglomerate, inside of which deformation is limited to fractured and re-healed cobbles, with no evidence of pressure solution. Orientation of the anticline is not directly related to the direction of motion in the upper plate. The last known trend of the fold axis of the Blacktail anticline is N. 20-30 E. at Blacktail Creek. This orientation places the Blacktail fold heading directly toward the area of Squaw Creek where the small footwall anticline occurs; in addition, there are SW-dipping beds in the Pilgrim Limestone below the footwall fold that are in the correct direction to be associated with one of the Blacktail's limbs. This orientation for the Blacktail anticline does not allow for the Squaw fold to be buttressed by either a limb of the Blacktail anticline or its nose. Striae on the fault plane several metres away from the Squaw anticline are S. 60 E., the expected direction of movement for the upper plate, and indicate that differential movement of upper-plate blocks did not cause a change in orientation for the local stress field. The origin of the Squaw anticline is probably due to an asperity from the Crandall Conglomerate, but the underlying structure that caused its orientation remains unclear.

Brecciation is the most common form of footwall deformation at the microscopic level. Most footwall breccia appears to be derived in-place, with fragments fitting back together well. There is evidence of fault-plane microbreccia injecting into the footwall in several areas. In thin section these injections appear as dark, fine-grained wedges protruding into the fine-grained carbonate footwall. Carbonate clasts, glass blebs, and plagioclase laths are all found within these injections, with the amount of carbonate increasing with depth into the footwall. In an area of the footwall with an anomalously large amount of injections there are areas of very-fine-grained wispy calcite that appear to be pressed up against the walls of fractures by injected material. These calcite wisps are possibly an expression of calcite that had dissociated due to frictional heating and then reconstituted when exposed to CO_2 gas in the volcanic microbreccia injection (E. Beutner, personal communication).

DISCUSSION AND CONCLUSIONS

Observations, field data, and thin sections confirm that brittle deformation was the sole mode of deformation on the Heart Mountain detachment. Contrary to previous studies, deformation immediately below the Heart Mountain Fault is not rare; however, it generally takes the form of footwall brecciation on the scale of 1-3 cm pods along fractures, or where deformation is more severe, a layer of cataclasis ranging from just centimetres to a metre thick. Pods of footwall breccia are likely due to slight motion on fractures during settling, whereas more extensive cataclasis found at several locations is more likely due to the faulting event itself.

Even where deformation is most severe, it has still occurred in a brittle manner. This, in addition to the distinct lack of deformation in many areas of the footwall, fits with brittle catastrophic faulting accompanied by the cushioning effect of a fluidized layer. As first suggested by Schoenbohm (1997), fanning fractures are clearly formed by anomalies along detachment surfaces, another line of evidence supporting catastrophic faulting. The only known fold in the footwall (first described by Hauge, 1984) shows internal brecciation rather than ductile deformation. This aberration from typical footwall fracturing and brecciation is likely the result of extra strain loading due to the fault's attempt to propagate through the competent and unbedded Crandall Conglomerate. The fault is rotated from its expected orientation possibly due to the influence of the Blacktail fold, which is associated with tilted Pilgrim strata beneath the Crandall Conglomerate.

A second goal of this study was to determine if inverse metamorphism in clays is present beneath hanging-wall plutons. This would be expected if the plutons were hot during emplacement as suggested in the model of volcanic fluidization with the Crandall Intrusive Complex utilized as a source for contemporaneous faulting and pluton injection (Beutner and Craven, 1996). There were no visible signs of metamorphism found at the three sites studied, and data from the X-ray diffraction of detrital clays within the footwall do not show significant differences in d-spacing or FWHM approaching the fault plane. These data suggest that upper-plate plutons were not hot enough to affect footwall clays at any measurable distance from the footwall, or that clays found in the footwall are not able to record such a low grade of metamorphism.

REFERENCES

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

Deer, W.A., Howie, R.A., and Zussman, J., 1962, Rock forming minerals, v. 3, The sheet silicates: New York, John Wiley [and Sons], 270 p.

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: Geological Survey of Wyoming, Cheyenne, Wyoming, p. 530-571.

Moore, D.M., and Reynolds, R.C., 1989, X-Ray Diffraction and the Identification and Analysis of Clay Minerals: New York, Oxford University Press, 332 p.

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

Schoenbohm, L., 1997, Footwall deformation in the bedding-parallel portion of the Heart Mountain detachment, northwestern Wyoming, in Mendelson, C. V., and Mankiewicz, C., eds., Tenth Keck Research Symposium in Geology Proceedings, p. 142-145.