ABSTRACT

White Mountain is centrally located in the bedding-plane portion of the Eocene Heart Mountain detachment and contains the only upper plate Mississippian Madison Group rocks that have been metamorphosed into marble. The marble rests upon the thickest (1 m) part of a carbonate ultracataclasite that marks the detachment. Thermodynamic and mechanical calculations based on possible frictional melting of calcite and other minerals, geochemical data, the characteristics of the carbonate ultracataclasite, and the geometrical characteristics of White Mountain suggest a possible initial upper plate emplacement rate of 126–340 m/sec and that the duration of the emplacement event was less than 4 min, too brief a time to develop an emplacement-related calcite twinning strain overprint in upper or lower plate carbonates. While the detachment-related carbonate ultracataclasite did not form by melting, it does preserve a magnetic fabric where K_max is parallel to the detachment slip direction and records a westward and down paleopole (287° and 27°), where magnetite is the carrier mineral. The Eocene (49.6 Ma) paleopole for this latitude in North America was southerly and upward (0° and 45°). This brief and catastrophic detachment event produced a significant amount of CO_2 by flash heating. This report is the first to quantify the emplacement rate of the upper plate of the Heart Mountain detachment based on physical and geochemical parameters.

Keywords: Heart Mountain detachment, calcite strains, paleomagnetism, thermodynamics, flash heating.

INTRODUCTION

The Heart Mountain detachment is a rootless, low-angle normal fault that accommodated transport of upper plate rocks for distances of as much as 30 mi (50 km) or more (Hauge, 1993). Transport was largely southeastward, from the northeast flank of the northern Absaroka Mountains, an Eocene volcanic center and basement uplift, toward and into the western margin of the Laramide-age Bighorn Basin. The detachment is preserved over an area of at least 1300 mi² (3400 km²) and formed in the middle Eocene, as the final stages of Laramide tectonism came to a close. Heart Mountain faulting involved rocks ranging in age from Ordovician to lower-middle Eocene but mostly Paleozoic cratonic strata and Eocene andesitic volcanic rocks of the Absaroka Volcanic Supergroup. The emplacement of the Heart Mountain allochthon was broadly contemporaneous with widespread igneous activity in the Absaroka volcanic province.

Various models have been proposed to explain the dynamics and kinematics of the Heart Mountain detachment, including rapid tectonic denudation (Bucher, 1933, 1947; Pierce, 1957, 1973, 1987), the slow-moving continuous allochthon (Hauge, 1982, 1985), volcanic collapse (Malone, 1993, 1994, 1995, 1996), and a rapid continuous allochthon without demudation (Beutner and Craven, 1996; Beutner and Gerbi, 2005). Recent geochronologic studies have greatly narrowed the permissible time of Heart Mountain detachment activity to between 49.7 and 49.5 Ma (Rhodes et al., 2007; Feeley and Cosca, 2003; Smith et al., 2003), strongly suggesting catastrophic upper plate emplacement. The window for emplacement of the Heart Mountain detachment upper plate has been narrowed considerably (2.0 Ma in 1990 and 0.2 Ma today) since Hauge proposed the continuous allochthon model in 1995. More recent authors have argued for a catastrophic emplacement of the upper plate (e.g., Malone, 1995; Beutner and Craven, 1996; Craddock et al., 2000; Beutner and Gerbi, 2005; Aharonov and Anders, 2005; DeFrates et al., 2006; Rhodes et al., 2007; Anders et al., 2009; Malone and Craddock, 2008) than have argued for gradual emplacement (e.g., Templeton et al., 1995;
Hiza, 1999). None of these papers has attempted to rigorously quantify the emplacement rate of the upper plate.

Our goal at White Mountain was to investigate the emplacement history of this part of the upper plate using calcite twin strain analysis on limestone and calcite veins from the lower plate and upper plate marble, anisotropy of magnetic susceptibility (AMS) on the carbonate ultracataclasite as a proxy for syndetachment “flow,” and standard demagnetization techniques on the carbonate ultracataclasite. We also undertook a geochemical (X-ray fluorescence [XRF], X-ray diffraction [XRD], scanning electron microscopy—energy-dispersive spectrometer [SEM-EDS], and stable isotope) traverse across the detachment to constrain the fault zone chemistry, which allowed for thermodynamic computations based on frictional melting (as a potential end member) of calcite-on-calcite to constrain the amount and rate of motion of the upper plate that produced the carbonate ultracataclasite.

**PREVIOUS WORK**

**White Mountain**

White Mountain is among the most famous localities in the Heart Mountain detachment area. Kirchner (1962) was the first to map the White Mountain area in detail and engage in a petrographic study of the local Eocene intrusive rocks. Kirchner’s maps were incorporated into several geologic maps published by the U.S. Geological Survey (Pierce, 1965; Pierce and Nelson, 1968, 1971; Pierce et al., 1982) over the next 20 years. Discussions of the field relations and petrology of intrusive rocks in the White Mountain area are provided by Hughes (1970) and Nelson et al. (1972).

White Mountain (Figs. 1 and 2) represents a second-order complexity within the chaos of the Heart Mountain detachment system. White Mountain is an upper plate block of Mississippian Madison Group, now marble, resting upon 1 m of carbonate ultracataclasite (see terminology discussion below) marking the detachment. Ordovician Bighorn Dolomite forms the autochthonous footwall along the bedding-plane portion of the detachment, although at White Mountain only thin veneers of dolomite remain (<10 mm; too thin to show in Fig. 1) and the carbonate ultracataclasite rests predominantly on Cambrian Snowy Range limestone. Calcite and aragonite veins are present (parallel and normal to the detachment, respectively), and there is no marble in the lower plate. White Mountain is also composed of Wapiti volcanic rocks, folded marble, crosscutting mafic dikes, and an allochthonous trachyandesite stock.

**Heart Mountain Detachment Breccia Terminology**

What has been described as “detachment breccia” is composed largely of carbonate material up to 1 m in thickness, which occurs at the base of the upper plate in some localities on the bedding portion of the Heart Mountain detachment (Pierce, 1957, 1973; Beutner and Gerbi, 2005). Because lower plate rocks are undeformed, this breccia was interpreted by Pierce (1973, 1979) to have been derived from the upper plate as a “tectonic carpet” during its emplacement. Because little or no volcanic material was originally found in this breccia where it is overlain by volcanic rocks, Pierce (1973, 1987) argued that these volcanic rocks were deposited after emplacement of the upper plate and a period of tectonic denudation. In a number of areas, this breccia intrudes upper plate rocks as clastic dikes, whereby Pierce (1979), Pierce et al. (1991), and Tokarski et al. (1994), proposed a sedimentary origin for the breccia. In addition to the all-carbonate breccia, breccia of mixed-volcanic-carbonate (Nelson et al., 1972) and all-volcanic (Hauge 1985) compositions have been reported. Mixed volcanic-carbonate breccia occurs at the base of the upper plate at White Mountain. Beutner and Craven (1996), Beutner and Gerbi (2005), and Anders et al. (2009) reported the occurrence of accreted, rolled and mantled grains, and delicate glassy shards within the ultracataclasite at White Mountain and many other localities within the Heart Mountain detachment region. In order to avoid confusion in terminology, we will propose the use of the term “carbonate ultracataclasite” (CUC) based on our observations (>80% carbonate matrix and <10% country rock clasts) and geochemical analyses for all material previously referred to as Heart Mountain detachment breccia, micro-breccia, or basal layer.

**Timing and Emplacement Rate of the Upper Plate**

The rate at which the upper plate of the Heart Mountain detachment was emplaced has been in dispute for more than 70 yr. Bucher (1947) and Pierce (1957, 1973) envisioned a catastrophic emplacement (a matter of hours) for the upper plate in the context of tectonic denudation. Although the evidence for this interpretation was largely speculative (i.e., lack of erosion on an interpreted, tectonically denuded detachment horizon and the necessity for fractionally reduced sliding of individual upper plate blocks), most workers during the 1960s and 1970s assumed a catastrophic emplacement mechanism and rate. Hauge (1985, 1990) interpreted the upper plate to be emplaced gradually at a rate of a few centimeters per year as a continuous allochthon driven by gravity spreading rather than gravity sliding. Hiza (1999) provided some isotopic ages in the proximal areas of the Heart Mountain detachment that support a gradual emplacement, but field relations at the localities are ambiguous. Malone (1994, 1996) and Malone and Sundell (2000) interpreted volcanic and Paleozoic (Malone and Sundell, 2000) rocks in the distal areas of the Heart Mountain detachment to be a large debris-avalanche deposit and thus inferred a catastrophic emplacement rate. Beutner and Craven (1996), Beutner (2002), and Beutner and Gerbi (2005) proposed catastrophic emplacement without tectonic denudation because of accreted grains and delicate glassy shards along the detachment horizon. Based on an absence of a detachment-related, calcite twinning strain overprint in allochthonous and autochthonous rocks, Craddock et al. (2000) also proposed a catastrophic emplacement rate. This interpretation is valid with or without tectonic denudation. The role of dike intrusion into the upper plate before motion has been interpreted as a potential source of heat and structural instability that contributed to the localization of the Heart Mountain detachment (Aharonov and Anders, 2006). DeFrates et al. (2006) studied the AMS fabrics of igneous dikes that pervade allochthonous Paleozoic limestones at Cathedral Cliffs. They found that most dikes were intruded vertically rather than laterally in opposition to field observations of earlier workers. DeFrates et al., interpreted these dikes to be older than, and unrelated to, the emplacement of the upper plate blocks and also invoked a catastrophic emplacement rate.

The timing of Heart Mountain faulting is well constrained in the distal areas of the Heart Mountain detachment where upper plate rocks overlay Eocene strata of the Willwood Formation. Feeley and Cosca (2003) report a 40Ar/39Ar age of 49.5 ± 0.16 Ma for basal Jim Mountain lava at Jim Mountain, which is ~100 m above the Heart Mountain interval. Based on paleontological evidence in the North Fork Shoshone River Valley (Torres and Gingerich, 1985; Gunnell et al., 1992), Heart Mountain faulting must have occurred during the earliest Middle Eocene (Bridgerian age, Blackforkian subage; North American Land Mammal Age) between 50 and 49 Ma. Heart Mountain faulting correlates with a major desiccation horizon in the Laney Member of the Washakie Formation in the Green River Basin (Rhodes et al., 2007). Smith et al. (2003) reported 40Ar/39Ar weighted mean ages of tuffs overlying and underlying the desiccation horizon to be 49.70 ± 0.10 and 48.94 ± 0.12 Ma, respectively. Near the breakaway area, Douglas et al. (2003) report 40Ar/39Ar ages on a variety
The Heart Mountain detachment is the world’s largest volcanic landslide.
Figure 2. (A) Carbonate ultracataclasite exposure on the west end of White Mountain, with calcite-twin sample sites (open circles). (B) Tom Hauge touching the Heart Mountain detachment at White Mountain. (C) Fault striations from the Heart Mountain detachment brachiopod for scale. (D) Photomicrograph of the Heart Mountain detachment with carbonate ultracataclasite above Bighorn from Jim Mountain site (see Beutner and Gerbi, 2005). Scale bar is 300 microns. CUC—“carbonate ultracataclasite.”
of small plutons between 48.1 ± 0.5 and 50.1 ± 0.3 Ma, within the age range of Heart Mountain detachment tectonism.

Assuming a maximum error in the reported geochronologic data, the time frame for Heart Mountain faulting is 49.34 to 49.80 Ma. Assuming all reported dates are reliable, Heart Mountain faulting would have had to have occurred between 49.70 and 49.50 Ma, which leaves 200 Ka as the time available for faulting and the deposition of some overlying and underlying rocks. A catastrophic emplacement of the upper plate is therefore likely. This report is the first to objectively quantify the emplacement rate of the upper plate based on physical parameters for materials generated along the detachment.

METHODS

Sampling and Methods

Oriented samples were collected throughout the west side of White Mountain (Fig. 2) including five samples of marble above the detachment, one limestone and two vein sets below the detachment (calcite twin analysis), and a continuous section of the 1-m-thick carbonate ultracataclasite zone (for AMS and paleopole determinations). The carbonate ultracataclasite, upper and lower plate limestones, and veins were analyzed using SEM-EDS, XRF, XRD, and stable isotope (C and O) techniques after extensive petrographic study.

Calcite Twinning

Calcite twins mechanically at low differential stresses (~10 MPa; see Lacombe and Laurent, 1992; Ferrill, 1998), and twinning is largely independent of temperature and normal stress magnitudes in the uppermost 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 at higher stress levels, provided that stress is oriented \(>45^\circ\) 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; Spang and Groshong, 1981; Wintiltscho et al., 1985; Craddock et al., 1993), calcite veins (e.g., Kilson and Wintiltscho, 1988), or, more rarely, marbles (e.g., Craddock et al., 1991). Amygdale and vein calcite in basalts also yield interpretable results (Deep Sea Drilling Project [DSDP] Hole 433C, Craddock and Pearson, 1994; Keweenaw rift, Craddock et al., 1997; Iceland, Craddock et al., 2004). Rowe and Rutter (1990) and Burkhard (1993) have recently reviewed the variety of methods applied for utilizing twinned calcite in a host of geologic environments.

The paleostress (paleopiezometry of Engelder [1993]) responsible for twinning can be calculated in terms of its compressional (or tensile) orientation (Turner, 1953) and magnitude (Jami-son 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% to 17% (Groshong et al., 1984). Strain magnitudes are a function of twin thickness and can vary greatly, depending on factors such as lithology, grain size, and porosity.

One to three thin sections were analyzed for each sample. Thin twins (~0.5 microns) are dominant in our sample suite and are characteristic of calcite deformed below 200 °C (Ferrill, 1991, 1998; Ferrill et al., 2004). The calcite strain gauge technique also computes positive and negative expected values (PEV and NEV, respectively) for all the twins in a given thin section. A NEV (negative expected value) for a twinned grain indicates that this grain was unfavorably oriented relative to the stress field that caused the twinning in the majority of grains in a given thin section. A high percentage of negative expected values (>40%) indicates that a second, non-coaxial twinning event occurred (Teufel, 1980).

Two twinning strains (PEV and NEV groups, respectively) can be analyzed separately.

AMS and Demagnetization Techniques

The “Roly-Poly” is an alternating-current (AC) susceptibility bridge with an automated sample handler for determining anisotropy of low-field magnetic susceptibility at room temperature. An AC in the external “drive” coils produces an alternating magnetic field in the sample space with a frequency of 680 Hz and amplitude of up to 1 mT. The induced magnetization of a sample is detected by a pair of “pickup” coils, with a sensitivity of \(1.2 \times 10^{-6}\) SI (International System of Units) volume units. For anisotropy determination, a sample is rotated about three orthogonal axes, and susceptibility is measured at 1.8° intervals in each of the three measurement planes. The susceptibility tensor is computed by least squares from the resulting 600 directional measurements. Very high precision results from the large number of measurements; in most cases, principal axis orientations are reproducible to within two degrees, and axial ratios to within ~1%. For each measured core, one unique magnetic ellipsoid is produced and plotted. Sample anisotropy percentages ranged from 2% to 17% for the 35 cores taken throughout the 1 m section. Fourteen cores were demagnetized to determine a paleopole signature for the CUC, ten by stepwise alternating-field (AF) methods, and four by thermal methods using Schoenstedt demagnetizers. Initially, one specimen from each site was demagnetized by each method, in five steps, and the results were used to determine the optimum demagnetization sequence for the remaining specimens. The magnetic carrier mineral(s) was determined using the vibrating-sample magnetometer (VSM), generating a hysteresis loop plot.

Geochemistry Methods

Stable isotopes were analyzed with a Finnigan MAT252 with a Kiel automatic carbon dioxide extraction unit at the University of Minnesota. Samples were reacted with 100% phosphoric acid for 300 s at 70 °C and compared to standards NBS-18 and NBS-19 from National Bureau of Standards (NBS) and LSVEC from National Institute of Standards and Technology (NIST) for carbon and oxygen and normalized to VPDB (Vienna Pee Dee belemnite).

X-ray fluorescence powders and analyses were done at Macalester College. Samples were split with a vise wedge, and only pieces lacking weathered or saw-marked edges were used in XRF analyses. Powders were prepared by further splitting the sample and reducing these pieces to a fine powder in a Spex 8510 shatterbox. The use of pre-contaminated bowls (iron for trace-element and tungsten carbide for major-element powders) reduced the chance of cross contamination between the samples. Pressed powder pellets were prepared for trace-element analyses by mixing 10 g of rock powder with 15 drops of 2% polyvinyl alcohol and pressing the mixture into pellets on a stainless steel mold under a pressure of 6 tons. Major-element concentrations were determined from fused glass beads that were prepared with dried sample powder that was mixed with lithium metaborate and tetraborate flux. The sample pellets and beads were analyzed using a Philips PW-2400 X-ray fluorescence spectrometer. Elemental concentrations were determined by comparing X-ray intensities for each element in a sample unknown with those from >40 international reference materials. Trace-element concentrations were corrected for matrix effects using the Rh tube Compton Kx scatter peak ratio method. Details of XRF sample preparation, analyses, analytical precision, and detection limits are provided in Vervoort et al. (2007). Powders and powder residues were analyzed using a PANalytical XPert Pro X-ray diffractometer.

Scattered electron micron (SEM) work was done with a JEOL JSM-6500F instrument with energy-dispersive spectrometer (EDS) and
RESULTS

Petrography and SEM Observations

The CUC is preserved as a promontory on the southwest side of White Mountain, directly above a sliver of Ordovician Bighorn Dolomite and Cambrian Snowy Range Limestone (Fig. 2B). The detachment (N64°E and 2° SE) is grooved and striated in the plane, with the strike trending 154° (Fig. 2C). The contact between the CUC and the footwall is sharp, and there is evidence of cataclasis in the footwall and of downward intrusion of CUC material (Fig. 2D), although in places along the bedding-plane portion of the detachment the footwall is pristine (Beutner and Gerbi, 2005). The 1-m-thick CUC is a dense, isotropic material that appears (and sounds, when hit with a hammer) well lithified. Internally, the CUC zone is a chaotic mix of volcanic clasts, glass shards, mantled lapilli, and limestone fragments, all hosted in a tight, dark matrix of microcalcite (>80%) that is locally layered parallel to the detachment. X-ray diffraction of bulk and acid-residue matrix samples revealed the presence of calcite, dolomite, aragonite, and serpentine (lizardite). Zerkle et al. (1999) report similar minerals, including siliceous fullerenes, which we did not identify. Twenty-nine AMS cores were measured for density, with a result of 3.01 g/cc. The melting temperature of powdered CUC is 1330 °C at 1 atm in a furnace.

Clasts (<5 mm) within the CUC contain evidence of pre detachment deformation with evidence of folding (Fig. 3A) in limestone clasts and abundant planar pressure-solution seams (Fig. 3B), and even reworking of the detachment (Fig. 3C). Most of the CUC is microcrystalline (<10 microns) carbonate cataclasite; the larger clasts are rounded limestone fragments (~ brucite; Fig. 3D) or combinations of armored, or lapilli, clasts with dolomite cores and calcite rims (or vice versa). These clasts are concentrically layered, not rolled like porphyroclasts. Some of these clasts contain internal alteration minerals (i.e., chloride and apatite) and alteration rims (i.e., illite and zeolites; Fig. 3E). Andesitic clasts constitute another, smaller population of large fragments (Figs. 4A and 4B). Numerous small (100 microns) plagioclase and hornblende crystal fragments are common (Figs. 4C and 4D) as are rare igneous glass shards, some of which include flow banding (Figs. 4E and 4F).

Less common, but widely disseminated in the CUC, are quartz and quartz-calcite spheroids. The quartz is commonly optically uniform, with fluid inclusions and a rim of microcrystalline calcite (Fig. 5A) or quartz (Figs. 5B and 5C). We also observe mixed plagioclase-calcite spheroids (Figs. 5D and 5E). There are no subgrain boundaries, deformation lamellae, or evidence of undulose extinction in these quartz spheroids. Reflective (metallic) phases are observable on thin section surfaces and, on inspection with the SEM-EDS, consist of a variety of iron-rich minerals (Fig. 6). Magnetite is the most common iron oxide (Fig. 6A; see paleomagnetism section below), with lesser amounts of goethite with marginal alteration minerals (Figs. 6C and 6D) and small, rare occurrences of pyrrhotite in calcite (Fig. 6B). The presence of fluids in the CUC is documented by the common observation of zeolite rims surrounding clasts and zeolites present in the cores of clasts, especially associated with plagioclase and hornblende (Figs. 7A and 7B). Also present are complex clasts of calcite, chlorite, and serpentine.

In the upper plate, most calcite grains contain two mechanical twin sets (see below) and are commonly intergrown with brucite (Figs. 8A and 8B) and, in some zones, brucite and forsterite (Figs. 8C and 8D). Closer to the Heart Mountain detachment, the marble contains brucite with euhedral inclusions of forsterite and, locally, possible calcioberarite (Figs. 8E and 8F). Crosscutting the CUC is a vein set (N40°W and 90°) that contains layered zones of complexly intergrown aragonite, serpentine, and minor calcite. One layer in the veins has an undulating shape with layer-normal aragonite blades with undulatory extinction (Fig. 9A). We observe delicate needles of serpentine filled with aragonite (and vice versa; Fig. 9B), as well as subtle Mg variations in zoned aragonite needles (Fig. 9C). The crosscutting relationship of these veins to the overlying marbles and underlying limestone is covered by scree.

Upper Plate Calcite Strains

Five oriented marble samples were collected above the detachment in 30 m intervals. Each sample preserves a layer-parallel shortening (LPS) strain with an average direction of shortening of 203°. For this one sample suite of 167 measurements, 49% (n = 81) had negative expected values with these examples preserving a twinning overprint that is a vertical, i.e., a bedding-normal shortening strain (Fig. 10; Table 1). Following the technique of Jamison and Spang (1976), we measured a compressive differential stress of ~37 MPa as being responsible for twinning the calcite.

Lower Plate Calcite Strains

The Cambrian Snowy Range Limestone below the Heart Mountain detachment also preserves this layer-parallel predetachment strain, but, because these rocks are autochthonous, the shortening axis is oriented E-W (Fig. 10; Table 1). There is no detachment-related twinning strain overprint at White Mountain, or elsewhere below the detachment (Craddock et al., 2000) because none of the samples has any significant NEVs. Following the technique of Jamison and Spang (1976), we measured a compressive differential stress of ~34 MPa as being responsible for twinning the calcite.

Vein Calcite Strains

One calcite vein (sample 22 from Craddock et al., 2000) is 1.6 m below, and parallel to, the detachment (Ed Beutner, 1996, personal communication) and preserves a vertical-shortening strain and no overprint (8% NEVs). The inferred differential stress responsible for this twinning is ~39 MPa using the technique of Jamison and Spang (1976). A second vein set was sampled at White Mountain from within the CUC zone. These vertical veins strike N40°W, are layered, 3–4 cm wide, and are composed of aragonite with a variety of textures, e.g., blades with undulatory extinction and perfect acicular needles (Fig. 9). Rare calcite is twinned but too uncommon for a twinning strain analysis. Exposure of the aragonite veins is obscured below the CUC, and the veins are not seen in the marble above; therefore, they are presumed to be contemporaneous with the Heart Mountain detachment.

Carbonate Ultracataclasite Anisotropy

Magnetic Susceptibility

Anisotropy of magnetic susceptibility (AMS) is a technique commonly applied to igneous materials, particularly mafic dikes, as a proxy for magmatic flow (Ernst and Baragar, 1992; Ernst and Duncan, 1995; Pawlisch et al., 1997; Kennedy and Craddock, 1999) often with clear results. We sampled continuously through the 1-m CUC section and analyzed 35 oriented cores using AMS. Sample anisotropy ranged between 7% and 21% and averaged 14%. The contoured maxima of the long axis of the magnetic ellipsoid (Kmax) is parallel to the observed slip direction along the detachment at White Mountain (154°) and plunges at ~30° to the detachment surface. The Kmax orientations are subvertical (33° and 65°), suggesting flattening within the plane of the detachment (Table 2; Fig. 10).

Carbonate Ultracataclasite Paleopole

Fourteen oriented cores from within the CUC were demagnetized (ten by alternating-field and four by thermal methods). The magnetic carrier
Figure 3. Clasts in the carbonate ultracataclasite that show evidence of pre–Heart Mountain detachment deformation. (A) Pressure-solution seams surrounding a small fold in Madison limestone; (B) a planar, layered clast with downward-increasing pressure-solution seams, perhaps a piece of plucked detachment, seen in (C) as a rounded clast of limestone (top) and carbonate ultracataclasite with pressure-solution seams. (D) Typical Madison limestone clast. (E) Typical mantled or rolled clast of calcite and dolomite. (F) Scanning electron micron (SEM) image of a clast with various primary and alteration mineral phases.
Figure 4. Andesitic volcanic clasts (A, with hornblende [larger arrow] and olivine [small arrow] and B), plagioclase (C, each crystal is ~100 microns long) and hornblende (D, each crystal is ~1 mm long) fragments and glass shards (E, folded; F) in the carbonate ultracataclasite.
The Heart Mountain detachment is the world's largest volcanic landslide.

Figure 5. Spherules of quartz + calcite (A–C; yellow arrow points to fluid inclusions), and plagioclase + calcite (D–F). D includes scanning electron micron (SEM) inset. C—calcite; Q—quartz; P—plagioclase. Each spherule is ~100 microns in its longest dimension.
Craddock et al.

mineral is single-domain pseudomagnetite and preserves a single-domain magnetization that is westward and down: 287° and 26° for alternating field ($\alpha_{95} = 6; K = 12$) and 295° and 41° for thermal demagnetization ($\alpha_{95} = 13; K = 18$). One result plotted in the upper hemisphere with the same westward declination. Our expectation was to find a southerly and upward signature for materials generated and quenched in the Eocene (49.6 Ma) at this latitude in North America (Table 2; Fig. 11).

Geochemistry Profiles

The Heart Mountain detachment is located in the lower Bighorn Dolomite within the bedding-plane portion of the system, the strongest unit in the section, and the least likely horizon in which to localize a detachment. Zenger (1992, 1996) has reported evaporite zones in Wyoming in the Bighorn Dolomite; thus, we attempted to identify sulfate and phosphate minerals in the profile at White Mountain as a means to explain the location of the detachment. X-ray fluorescence was used to identify major- and trace-element concentrations in the marble, CUC, and footwall Snowy Range Limestone. We did not find evidence of evaporite minerals or major- (i.e., high Na$_2$O, K$_2$O, or P$_2$O$_5$) or trace-element concentrations as described by Zenger (1992, 1996). Major-element concentrations preserve enrichment in the CUC, compared to the lower limestone and overlying marble, of SiO$_2$ (7.5% versus 0.58%–1.6%), TiO$_2$ (0.1% versus 0.01%), Al$_2$O$_3$ (2.0% versus 0.2%), FeO (1.1% versus 0.5%), MnO (0.02% versus 0.01%), Na$_2$O (0.1% versus 0.03%), K$_2$O (0.35% versus 0.015%), and P$_2$O$_5$ (0.06% versus 0.02%). Trace-element concentrations in the CUC show enrichment of BaO (144 ppm versus 0), Cr$_2$O$_3$ (28 ppm versus 0 ppm), Cu (20 ppm versus 15), Ni (11 ppm versus 7 ppm), Ga (5.8 ppm versus 4.0 ppm), Rb (14 ppm versus 5.5 ppm), and Zr (7.2 ppm versus 0 ppm). The aragonite vein is enriched in Sr, Ni, and Zn. Concentrations of Ce, Co, Sc, V, Zn, Nb, Th, U, and Y are consistent throughout the section, whereas Pb and Sr show significant variations (Table 3). Stable isotopes (C and O) were also analyzed in the marble ($\delta^{13}$C = −2.94, $\delta^{18}$O = −6.65 versus PDB), CUC matrix (−2.37 and −9.32), the aragonitic

Figure 6. (A) Pyrrhotite fragments in calcite; backscattered electron (BSE) image. (B) Magnetite clast in the carbonate ultracataclasite. (C) Goethite clast showing reaction rim within the carbonate ultracataclasite; picture processing language (PPL) image. (D) Close-up view of goethite clast from (C); backscattered electron (BSE) image.
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Vein that crosscuts the CUC (0.33 and −10.72), and the footwall limestone (0.2 and −9.29; Table 4). The aragonite veins contain small (1- to 3-micron), dark, apparently single-phase, vapor-dominated fluid inclusions; they are too small to observe phase changes and presumably contain CO₂ and some H₂O.

**DISCUSSION**

**Friction-Induced Flash Heating**

Landslide deposits are generally small (~10 km²) and are associated with oversteepened slopes in orogenic belts where seismicity and local precipitation play a role in failure. Sturzstrom formation can involve wholesale disaggregation of a rock body, or shear zones, throughout a failing rock body as it moves downslope (Pollet and Schneider, 2004), and the basal shear zone (see Hewitt, 1988) is characterized by a layered media that is graded or inversely graded (Anders et al., 2000, 2009). The Heart Mountain detachment landslide is unique for its enormous areal extent (3400 km²), the distant motion of slide blocks (~50 km), the motion of some slide blocks over Rattlesnake Mountain (500 m elevation along the detachment), the coeval nature of andesitic volcanism and dike intrusion, and the localization of deformation only along the detachment. Marble-on-marble frictional studies of fault displacements by Han et al. (2007), with fault normal stresses of ~7 MPa (70 bars), result in fault displacements of ~1–2 m/sec that produce a nanometer-size calcite fault gouge of CaO (melting T° = 2572 °C) and release extraordinary amounts of CO₂ (29,000 ppm) along a fault boundary with a temperature of ~900 °C. The degradation of calcite by this process is known as “flash heating,” and these results are consistent with some of our Heart Mountain detachment observations.

**White Mountain Emplacement**

White Mountain is the most peculiar component of the enormous, chaotic Heart Mountain detachment system. The Mississippian Madison Group preserves a predetachment, layer-parallel Laramide shortening strain that was subhorizontal and oriented E-W (Craddock et al., 2000). The White Mountain allochthon, now a Madison Group marble, rotated a minimum of 113° clockwise (or 247° counterclockwise) from 90° to 203°, which is the orientation of the shortening axis today. This rotation likely occurred early in the detachment history, upstream to the northwest, because detachment striations are all to the SE (154°), although there is evidence of clast rotation on many striated Heart Mountain

![Image](https://example.com/image.png)

**Figure 7. Reaction rims on and in clasts within the carbonate ultracataclasite.**

(A) hornblende, with twins, zeolite alteration, and a reaction rim. (B) A calcite clast with mixed internal alteration and a reaction rim. (C) Backscattered electron (BSE) image of hornblende clast in (B) showing partial replacement by serpentine, chlorite, and illite.
Figure 8. Upper plate Mississippian Madison Group marble A and B; C and D are plane light (left) and polarized light (right) pairs showing calcite (twinned)-brucite intergrowth (A and B) and calcite-brucite + forsterite (C and D). (E) Close-up of forsterite in brucite (arrows) and rare calciobetafite along brucite rims (F). C—calcite; B—brucite; arrows point to forsterite.
The Heart Mountain detachment is the world’s largest volcanic landslide.

Figure 9. Aragonite vein that crosscuts the carbonate ultracataclasite. (A) The vein is layered with a radiating texture and undulatory extinction (polarized light); finer grained layers include a mixture of aragonite (light) cores within serpentine (gray) needles delicately intergrown (B) and subtle Mg/Ca variations within magnesium calcite prisms (C). B and C are scanning electron micron (SEM) images.
Figure 10. Stereoplots of upper plate (top, A and B), carbonate ultracataclasite (middle, C and D) and lower plate (bottom, E and F) fabric data. Lower-hemisphere plots of calcite twin analyses (A and B and E and F) with contours of Turner (1953) compression axes and strain axes (ε1—shortening axis; ε2—intermediate axis; ε3—extension axis). Heart Mountain detachment is plotted with anisotropy of magnetic susceptibility (AMS) results in C (K_max) and D (K_min) and the net slip direction along the Heart Mountain detachment. NEV—negative expected value; PEV—positive expected value.
The Heart Mountain detachment is the world’s largest volcanic landslide

TABLE 1. WHITE MOUNTAIN CALCITE TWINNING STRAINS

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock unit</th>
<th>Location</th>
<th>Grains (n =)</th>
<th>e1</th>
<th>e2</th>
<th>e3</th>
<th>e4</th>
<th>e5</th>
<th>NEV</th>
<th>Δσ</th>
<th>Fabric interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Marble (lowest)</td>
<td>UP</td>
<td>33</td>
<td>26°, 7°</td>
<td>111°, 15°</td>
<td>201°, 85°</td>
<td>-6.5</td>
<td>54</td>
<td>-37.3</td>
<td>LPS</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Marble</td>
<td>UP</td>
<td>34</td>
<td>212°, 9°</td>
<td>298°, 11°</td>
<td>122°, 82°</td>
<td>-3.7</td>
<td>24</td>
<td>-38.2</td>
<td>LPS</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Marble</td>
<td>UP</td>
<td>36</td>
<td>18°, 12°</td>
<td>287°, 9°</td>
<td>109°, 83°</td>
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<td>41</td>
<td>-47.1</td>
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<tr>
<td>4</td>
<td>Marble</td>
<td>UP</td>
<td>27</td>
<td>23°, 14°</td>
<td>296°, 5°</td>
<td>114°, 87°</td>
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<td>26</td>
<td>-30.8</td>
<td>LPS</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Marble (highest)</td>
<td>UP</td>
<td>37</td>
<td>200°, 5°</td>
<td>291°, 7°</td>
<td>112°, 83°</td>
<td>-5.1</td>
<td>35</td>
<td>-35.7</td>
<td>LPS</td>
<td></td>
</tr>
<tr>
<td>Combined NEV</td>
<td>Marble</td>
<td>UP</td>
<td>85</td>
<td>203°, 3°</td>
<td>123°, 7°</td>
<td>351°, 83°</td>
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<td>0</td>
<td>LPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined PEV</td>
<td>Marble</td>
<td>UP</td>
<td>81</td>
<td>1°, 86°</td>
<td>67°, 3°</td>
<td>137°, 9°</td>
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<td>100</td>
<td>LNS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Footwall limestone</td>
<td>LP</td>
<td>36</td>
<td>91°, 2°</td>
<td>1°, 3°</td>
<td>225°, 87°</td>
<td>-3.5</td>
<td>5</td>
<td>-34.6</td>
<td>LPS</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Footwall vein</td>
<td>LP</td>
<td>26</td>
<td>6°, 85°</td>
<td>85°, 8°</td>
<td>178°, 12°</td>
<td>-7.2</td>
<td>8</td>
<td>-39.8</td>
<td>LNS</td>
<td></td>
</tr>
</tbody>
</table>

Note: All samples have horizontal orientations.
Abbreviations: LNS—layer-normal shortening; LPS—layer-parallel shortening; UP—upper plate; LP—lower plate; NEV—negative expected value; PEV—positive expected value.

TABLE 2. WHITE MOUNTAIN MAGNETIC DATA

<table>
<thead>
<tr>
<th>Sample</th>
<th>Anisotropy</th>
<th>Hysteresis</th>
<th>Fabric interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUC (microbreccia)</td>
<td>35</td>
<td>1.16</td>
<td>-</td>
</tr>
</tbody>
</table>

Detachment Dynamics

Our first analysis below is based on the interpretation that the fault-generated carbonate material along the Heart Mountain detachment was a calcareous melt generated by frictional motion between carbonates, and this is intended to demonstrate a frictional melting, end-member scenario. The second, and more appropriate analysis, utilizes the bulk composition and various minor melt indicators (lower than the 1339 °C required to melt calcite) in the CUC as a way to constrain the temperature along the detachment and thereby constrain the upper plate rates of motion. For the first analysis, we assume the CUC was a full calcareous melt (i.e., resulting in the formation of “pseudotachylite”); calcite has a melting T° of 1339 °C at 1 atm), something unreported in the literature since 1999. Therefore, we can use the model to predict the sliding distance, and compare these results to the observed location of White Mountain. We assume that the 1 m CUC (“melt”) layer was formed as a result of frictional heating as the limestone blocks slid along detachment surfaces (Fig. 2C; Beutner and Gerbi, 2005). We have no way to constrain the number of rotational increments about a vertical axis experienced by White Mountain in transit, but the block slid to rest with the LPS fabric oriented at 203° while sliding toward 154°. The localized transformation into marble must be predetachment and the result of contact metamorphism near the Crandall volcano, especially as the footwall limestone is unaffected and there are no marble (+ brucite + forsterite) clasts in the CUC. Motion along the bedding-parallel portion of the Heart Mountain detachment generated a veneer of carbonate ultracataclasite that is thickest and best preserved at White Mountain. The composition of the CUC is generally more siliceous (7.5% SiO₂) carbonate (Table 3) than the hanging and footwall carbonates, indicating that eruption of the Crandall volcano was contemporaneous with initiation of the detachment. Our stable isotope results are consistent with values reported by Templeton et al. (1995) and Douglas et al. (2003) and suggest that meteoric and magmatic fluids were important in facilitating motion along the Heart Mountain detachment. The well-lithified (welded and sintered) nature of the CUC encases the variation of clast reaction rim mineralogy and textures (Figs. 3, 5, and 7), again requiring a significant fluid phase to have been present during deformation. Some carbonate clasts preserve pressure-solution seams parallel to bedding, indicating an early, slower deformation phase (Figs. 3A–3C), and these clasts have been reworked by the chaos that formed the CUC, including the movement of multiple upper plate blocks sliding over a given portion of the detachment. Within the CUC, we observe glass shards that may or may not be mantled (armored), clasts that are mantled, and a detachment-parallel grading. If the Heart Mountain detachment catastrophe involved multiple slide and eruption events, we would expect to see broken armored clasts that were remanent as well as offsets to the CUC layering. None of this is observed at White Mountain, or elsewhere in the CUC (Beutner and Gerbi, 2005; Anders et al., 2009), indicating the Heart Mountain detachment was a one-time event. The CUC is enriched in all major and trace elements, except Sr (Sr87/Sr86 was not measured; see Anders et al., 2009), as compared to the autochthonous footwall limestone, again indicating magmatic (volcanic clasts) or meteoric (fluid phase) additions during deformation.

The CUC also preserves a magnetic (AMS) fabric with the long axis of the magnetic ellipsoid plunging 30° to the detachment and parallel in trend to the slip direction (Fig. 2C). The CUC and underlying limestones are crosscut by vertical veins of Sr-rich aragonite with complex textures and horizontal veins of twinned calcite. Little can be made of these observations because there is a paucity of literature on deformation mechanisms in aragonite. The paleomagnetic result in the CUC (down and westward paleopole; see also Gerbi [1999] and below) is difficult to explain, but magnetite clearly exceeded its Curie temperature when the detachment was active. After White Mountain came to rest and was buried by subsequent volcanic deposits, the burial load twinned the detachment-parallel calcite veins and imposed a second, vertical-shortening twinning strain on the overlying marbles. Undulatory extinction is the only deformation present in the aragonite veins.
the fault plane. The energy required to heat, and then melt, the layer $W_m$ is given by:

$$\frac{1}{2} W_m = m_L C_p (T_m - T_0) + m_L H_f,$$

where $T_m$ is the melting temperature, $T_0$ is the temperature at the initiation of the slide, $m_L$ is the mass of the melt layer, $C_p$ is the heat capacity, and $H_f$ is the heat of fusion. The factor of $\frac{1}{2}$ is inserted since it is assumed that half of the heat generated by friction is dissipated in the plane. The work done by sliding friction is given by:

$$W_w = \mu_k m_w g d_w,$$

where $\mu_k$ is the coefficient of sliding (kinetic) friction, $g$ is the acceleration due to gravity (9.8 m/s$^2$), $m_w$ is the mass of White Mountain, and $d_w$ is the sliding distance. Solving (1) and (2) for $d_w$ gives:

$$d_w = \frac{2 m_L C_p (T_m - T_0) + m_L H_f}{\mu_k m_w g}.$$

For $C_p$ and $H_f$, we use the values for CaCO$_3$ given as 819 J kg$^{-1}$ deg$^{-1}$ and 528,000 J kg$^{-1}$, respectively, from reference [CRC 90–91]. The masses of the 1 m interval and of White Mountain are $\rho A_B$ and $1/3 \rho A_B h$ (a conical shape), respectively, where $\rho$ is the mass density of limestone (taken as 2500 kg m$^{-3}$), $A_B$ is the area of the base (2.2 km$^2$), and $h$ is the height (500 m). Recent laboratory work on carbonate faults indicates that at fast slip rates, $>1$ m/s, the coefficient of friction can be quite low, ~0.06 (Han et al., 2007). $T_m$ is assumed to be approximately the melting temperature of 1640 °K, and $T_0$ is taken as 300 °C. Both of these temperatures are likely to be very approximate, since it is quite possible that the slab does not start at ambient temperature, if it is proximal to the Crandall volcano, and the temperature at which

Figure 11. Paleomagnetic results for the carbonate ultracataclasite at White Mountain. (A) Hysteresis plot, indicating single-domain magnetite is the magnetic carrier mineral. (B) Magnetic time scale for the early Eocene, including the age of the Heart Mountain detachment (49.6 Ma; see text). (C) Combined alternating-field (AF) ($n = 10$; solid triangle) and thermal ($n = 4$; open triangle) demagnetization results compared to the expected Eocene paleopole (open circle—reversed polarity; closed circle—normal polarity) from (D) representative Zijderveld plot for an AF demagnetization.
melting or metamorphism occurs under these specific conditions is unknown. In addition, we are making a tacit assumption that the 1 m layer has a uniform temperature profile. We should also note that once the limestone begins to melt or otherwise begins to metamorphose, the coefficient of friction might also change.

With these values and assumptions, we find that \( d_m = 33 \text{ km} \). This result compares well with the observed value of 24 km, given the approximations of the model. As we discuss below, it is likely that the limestone does not actually melt, so this result represents an upper limit to the distance traveled. Two other parameters can be extracted from this model. First, if we assume that the work done by friction is equal to the initial kinetic energy of the mountain, as it should be according to the work-energy theorem, then we have:

\[
\frac{1}{2} \mu_w v^2 = \mu_s m_w g d_w.
\]  

Solving the equation for the parameters given above yields \( v_s = 198 \text{ m/s} \) for the initial speed of White Mountain. The time it takes to come to rest can be determined from:

\[
d_m = v_s t - \frac{1}{2} \mu_s g t^2,
\]

yielding \( t = 340 \text{ s} \) or \(-5.7 \text{ min}\). Energy loss due to rotation is minimal in this analysis. The significance of this result is that twinning in calcite is time dependent, and there is no twinning strain overprint in the system (Craddock et al., 2006); therefore, upper plate block motion must have been rapid. Our result is an upper limit for plate motion and is somewhat more than half the speed of sound.

A similar analysis can be applied to Heart Mountain. In that case, the model can be used to predict the expected thickness of a “melt” layer, given the distance Heart Mountain is from the breakaway area. Taking the base area and height given the distance Heart Mountain is from the modern and ancient detachment from marine carbonate and a magmatic source beneath the detachment (Templeton et al., 1995; Douglas et al., 2003). The population of alteration minerals (zeolites [heulandite and laumontite], illite, chlorite, etc.) indicates the presence of water during fault motion with a temperature \( \sim 250 ^\circ \text{C} \). A number of textures also suggest some mineral phases were melt droplets: quartz and quartz-calcite spheres (melt \( T^o = 600 ^\circ \text{C} \)), pyrrhotite in calcite (melting \( T^o = 900 ^\circ \text{C} \)), and goethite “spheres.” Delicate, igneous glass shards remain preserved, although some are abraded and rounded, and the quartz spheres are most likely crystalized siliceous vapors of igneous origin (\( T^o = 1000 ^\circ \text{C} \)) rather than vesicle fillings or detrital grains in an ultracataclasite. Quartz spheres are present, and some contain fluid inclusions, but they are undeformed. Pseudotachylite is known in nearby igneous plutons in the upper plate (Bettner and Craven, 1996). The AMS fabric also suggests preservation of a cataclastic flow in the direction of upper plate transport. Magnetite is the magnetic carrier, which clearly was remagnetized during fault motion; therefore, the CUC temperature exceeded \( 575 ^\circ \text{C} \). Han et al. (2006) report siderite-to-magnetite phase transitions during carbonate fault experiments. Stable isotope results also indicate a local metamorphic fluid fractionation along the Heart Mountain detachment from marine carbonate and a magmatic source beneath the detachment (Templeton et al., 1995; Douglas et al., 2003). The aragonite veins are Sr rich and contain vapor-only fluid inclusions. We have no independent means to estimate the local geothermal gradient, but it was probably higher than 30 °C/km (average), being near the Crandall volcano. In sum, we suspect that the formation temperature of the CUC at White Mountain was \( \sim 600 ^\circ \text{C} \). This is considerably higher than the temperatures (400 °C) of Heart Mountain detachment.

---

TABLE 3. WHITE MOUNTAIN X-RAY FLUORESCENCE GEOCHEMISTRY

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<tr>
<th>Major elements (wt.%)</th>
<th>Snowy Range Limestone (versus Pee Dee belemnite)</th>
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<td>SiO₂</td>
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<tr>
<td>TiO₂</td>
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<td>Al₂O₃</td>
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<tr>
<td>Fe₂O₃</td>
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<tr>
<td>MnO</td>
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<td>MgO</td>
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<tr>
<td>CaO</td>
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<tr>
<td>Na₂O</td>
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<tr>
<td>K₂O</td>
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<tr>
<td>P₂O₅</td>
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<td>Cr₂O₃</td>
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<td>SrO</td>
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<td>ZrO</td>
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<td>CeO</td>
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<tr>
<td>LaO</td>
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<tr>
<td>PbO</td>
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<tr>
<td>ThO</td>
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<tr>
<td>UO</td>
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<td>Trace elements (ppm)</td>
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<td>Sc</td>
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<td>Detection limits</td>
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<td>LOI</td>
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Note: Loss on ignition (LOI) reported as percent weight change of pre-dried samples after sintering for one hour at 1000 °C.

Abbreviations: bd—below detection; Cr and Ba reported as ppm; CUC—“carbonate ultracataclasite.”

CUC Partial Melt Analysis

A more realistic approach is to evaluate the petrographic, mineralogic, and magnetic results to constrain a temperature for the CUC during formation. Clearly, there was not wholesale melting as limestone (marble) slid over limestone and dolomite, and the CUC is compositionally different. The CUC is more siliceous (7.5%) and is enriched in a number of major and trace elements, all indicative of the contemporaneous inclusion of andesitic materials into the Heart Mountain detachment system. The population of alteration minerals (zeolites [heulandite and laumontite], illite, chlorite, etc.) indicates the presence of water during fault motion with a temperature \( \sim 250 ^\circ \text{C} \). A number of textures also suggest some mineral phases were melt droplets: quartz and quartz-calcite spheres (melt \( T^o = 600 ^\circ \text{C} \)), pyrrhotite in calcite (melting \( T^o = 900 ^\circ \text{C} \)), and goethite “spheres.” Delicate, igneous glass shards remain preserved, although some are abraded and rounded, and the quartz spheres are most likely crystalized siliceous vapors of igneous origin (\( T^o = 1000 ^\circ \text{C} \)) rather than vesicle fillings or detrital grains in an ultracataclasite. Quartz spheres are present, and some contain fluid inclusions, but they are undeformed. Pseudotachylite is known in nearby igneous plutons in the upper plate (Bettner and Craven, 1996). The AMS fabric also suggests preservation of a cataclastic flow in the direction of upper plate transport. Magnetite is the magnetic carrier, which clearly was remagnetized during fault motion; therefore, the CUC temperature exceeded \( 575 ^\circ \text{C} \). Han et al. (2006) report siderite-to-magnetite phase transitions during carbonate fault experiments. Stable isotope results also indicate a local metamorphic fluid fractionation along the Heart Mountain detachment from marine carbonate and a magmatic source beneath the detachment (Templeton et al., 1995; Douglas et al., 2003). The aragonite veins are Sr rich and contain vapor-only fluid inclusions. We have no independent means to estimate the local geothermal gradient, but it was probably higher than 30 °C/km (average), being near the Crandall volcano. In sum, we suspect that the formation temperature of the CUC at White Mountain was \( \sim 600 ^\circ \text{C} \). This is considerably higher than the temperatures (400 °C) of Heart Mountain detachment.

---

TABLE 4. STABLE ISOTOPE RESULTS

<table>
<thead>
<tr>
<th>Sample</th>
<th>δ¹³C</th>
<th>δ¹⁸O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marble</td>
<td>-2.94</td>
<td>-6.65</td>
</tr>
<tr>
<td>“Carbonate ultracataclasite” (CUC)</td>
<td>-2.37</td>
<td>-9.32</td>
</tr>
<tr>
<td>Vein</td>
<td>0.33</td>
<td>-10.72</td>
</tr>
<tr>
<td>Snowy Range Limestone (versus Pee Dee belemnite)</td>
<td>0.2</td>
<td>-9.29</td>
</tr>
</tbody>
</table>

The Heart Mountain detachment is the world’s largest volcanic landslide.
CONCLUSIONS

White Mountain occupies a central portion of the bedding-plane portion of the Heart Mountain detachment, ~15 km downslope of the breakaway area. There are numerous upper plate slide blocks downslope of White Mountain, and many of these slide down the detachment to the southeast over the White Mountain site before the marbles (and igneous intrusions) of White Mountain came to rest after a horizontal rotation about a vertical axis. This process generated a carbonate ultratiltalcite along the Heart Mountain detachment in many locations (see Beutner and Gerbi [2005] and Anders et al. [2009]) that is thickest at White Mountain. None of the footwall rocks preserve a twinning strain related to Heart Mountain detachment motion. We do not observe any marble in the CUC; therefore, contact metamorphism near the Crandall volcano must have altered the Madison Group limestones to marble (~600 °C) before they arrived at White Mountain. Curiously, White Mountain is the easternmost oddity in a line of rootless, upper plate igneous intrusions (diorites, shoshonites, etc.) that extend westward to Crandall Creek (Beutner and Craven, 1996). The CUC contains a significant igneous signature supporting the coeval nature of Crandall volcanism and motion of Heart Mountain detachment blocks. On a regional scale, when considering the enormous scale of this landslide, it is remarkable that the CUC is generally only a few millimeters in thickness. We have also observed evidence of predetachment, pressure-solution deformation preserved in carbonate clasts in the CUC that indicates that deformation was localized along the plane that became the detachment prior to catastrophic motion of the upper plate. Eruption of the Crandall volcano likely involved inflation of the flank (see Siebert et al., 1987), probably increasing the dip of the future detachment while adding volcanic material, including enormous numbers of mafic dikes (see Aharonov and Anders, 2006; DeFrates et al., 2006) and water (H$_2$O$_{vapor}$). These two factors weakened the Bighorn Dolomite, thus giving the upper plate blocks a critical slope and a reduction in the coefficient of friction to initiate motion to the southeast. Using results from Han et al. (2007), we estimate a 15-million-ton release of CO$_2$ from motion along the bedding-plane portion of the detachment, an amount of CO$_2$ that would double the concentration in the entire atmosphere column over an area of 1700 km$^2$, or the equivalent CO$_2$ release from a modest volcanic eruption. The contemporaneous CO$_2$ contribution of the andesitic Crandall volcano eruption is unknown. The emplacement of upper plate blocks lasted 3–4 min. The final deformation at White Mountain was a vertical-shortening strain preserved in the upper plate marbles and lower plate, detachment-parallel calcite veins imposed by volcanic burial. Thus, the gradual emplacement rate (a few cm/yr) of a “continuous allochthon” as suggested by Hauge (1985, 1990) is not supported by these data. A modified view of a “rapid continuous allochthon” model as advocated by Malone (1995) or Beutner and Gerbi (2005), each of which requires the catastrophic emplacement rate determined herein, is preferred.

ACKNOWLEDGMENTS

Ed Beutner graciously provided the oriented, lower plate, detachment-parallel vein sample. Craddock also greatly benefited from the interactions provided during the Geological Society of America trip to the Heart Mountain area organized by Dave Malone, Tom Hauge, and Ed Beutner (October, 1999). Cook was supported by the Keck Foundation and Rieser by the Beltmann Fund, Macalester College. Mike Jackson, Institute for Rock Magnetism, Colgate University, graciously investigated the aragonitic vein fluid inclusions. Conversations with Eric Ferre, Eric Essene, Peter Hudleston, Dave Kohlstedt, Raehee Han, and Keith Kuwata and reviews by Mark Anders, Rick Groshong, Peter Eichhubl, and Neil Mancktelow are greatly appreciated.

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