Spring 5-2012

A Mineralogical Textural and Chemical Characterization of a Hypothesized Kimberlite at White Mountain, Sunlight Basin, Wyoming

Stuart Kenderes
Western Kentucky University, stuart.kenderes470@topper.wku.edu

A MINERALOGICAL TEXTURAL AND CHEMICAL CHARACTERIZATION OF A HYPOTHESIZED KIMBERLITE AT WHITE MOUNTAIN, SUNLIGHT BASIN, WYOMING

A Capstone Experience/Thesis Project

Presented in Partial Fulfillment of the Requirements for

the Degree Bachelor of Science with

Honors College Graduate Distinction at Western Kentucky University

By

Stuart Kenderes

*****

Western Kentucky University
2012

CE/T Committee:

Professor Andrew Wulff Ph. D, Advisor

Professor Lester Pesterfield Ph. D

Professor Dennis Wilson Ph. D

Approved by

____

Advisor
Department of Geography & Geology

ABSTRACT

Geologists have examined the causes and mechanisms responsible for the Heart Mountain detachment for over a century with much debate and discussion. White Mountain is a part of the upper plate, which was emplaced during the detachment event. Within White Mountain, there exist several andesitic dikes and carbonate ultra-cataclasite injectites, which were integral in the emplacement of the Heart Mountain detachment. This research involves the characterization and identification of an enigmatic vertical outcropping of brecciated rock located on White Mountain, Sunlight Basin, Wyoming, which was originally interpreted as a kimberlite. Samples were collected for geochemical and textural comparison, and cut into thin sections for analysis using polarized light microscopy. Remaining sample material was powdered for X-ray fluorescence geochemical analysis and for heavy mineral splits for U-Pb dates of primary zircons. Geochemical results indicate the enigmatic unit more closely resembles local andesitic dikes, while textural observations show two different rock types.

Keywords: Geology, Wyoming, Heart Mountain detachment, White Mountain, Kimberlite, Absaroka Range

ACKNOWLEDGMENTS

Funding for this project was provided generously by the Keck Geology Consortium, the National Science Foundation, Exxon-Mobile Inc., and the USGS Ed-Map program. Special thanks go to my advisors Drs. John Craddock and David Malone in the field, and Dr. Andrew Wulff at my home institution of WKU. I would also like to thank my fellow students who participated in the REU, and helped collect samples and provide moral support. They include, Andrew Kelly, Ben Kraushaar, Ali MacNamee, Maren Mathisen, Kat Schroeder, and Jamie Bardwell.

VITA

2012 .... Bachelor of Science, Western Kentucky University, Bowling Green, Kentucky

2011.. Research Experience for Undergraduates, Keck Geology Consortium

2007.. Simon Kenton High School, Independence, Kentucky

PUBLICATIONS AND PRESENTATIONS

Kenderes, S.M., Wulff, A.H., 2012, Mineralogical, textural, and chemical characterization of a hypothesized kimberlite at White Mountain, Sunlight Basin, Wyoming: Keck Geology Consortium Spring Symposium Journal.

Kenderes, S.M., Wulff, A.H., 2012, Mineralogical, textural, and chemical characterization of a hypothesized intrusion at White Mountain, Sunlight Basin, Wyoming: WKU Student Research Conference, Bowling Green, KY, p.20 Abstracts.

Price, B., Kenderes, S.M., 2012 A petrographic analysis of a transgressive limestone: WKU Student Research Conference, Bowling Green, KY, p.25, Abstracts.

MacNamee, A., Kravitz, K., Kenderes, S.M., Mathisen, M., Malone, D.H., 2011 New insights on the structural evolution of the Eocene South Fork detachment: Geological Society of American Annual Meeting, Minneapolis, MN, Vol. 43, No. 5, p.115, Abstracts.

Kenderes, S.M., Siewers, F., 2010, A petrographic and Raman microscopy study of the fibrous carbonates in coal ball concretions: toward an enhanced understanding of high magnesian calcite diagenesis: 96th Annual Kentucky Academy of Science Meeting, Bowling Green, KY, Abstract. ***3rd Place Poster Presentation***

Kenderes, S.M., Crowder, M., 2009 Examination of geoscience education practices: 95th Annual Kentucky Academy of Sciences Meeting, Highland Heights, KY, Abstracts. ***1st place Oral presentation***

FIELD OF STUDY

Major Field: Geology

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

CHAPTER 1

INTRODUCTION

The Heart Mountain detachment (HMD) has been described as the largest subaerial landslide exposed currently on the Earth's surface (Pierce 1975, Beutner 2009). There have been several hypothesized emplacement mechanisms described such as a tectonic denudation model, a slow-moving continuous allochthon model, a volcanic collapse model, and a rapid-moving continuous allochthon model. Each model has been met with disagreement until recently.

It is now believed that the HMD has occurred during the middle Eocene, with best age estimates between 49.3 and 49.8 mya. The feature covers an area of 3,400 km^2 (Hauge 1990) extending from the northeast corner of Yellowstone National Park southeastward to Heart Mountain and McCulloch Peaks (Pierce 1957). The emplacement rate of the detachment is described as between 126-340 m/s (Craddock et al. 2009), indicating the event only lasted 3-4 minutes. The detachment occurs along four different fault types including a high-angle breakaway fault, a bedding plane fault, a transgressive fault, and a low angle fault (Pierce 1975). Upper plate blocks were emplaced along a low-angle fault as much as 50 km from their source (Malone 1999). This fault occurs on average 2-3 meters above the base of the Bighorn Dolomite

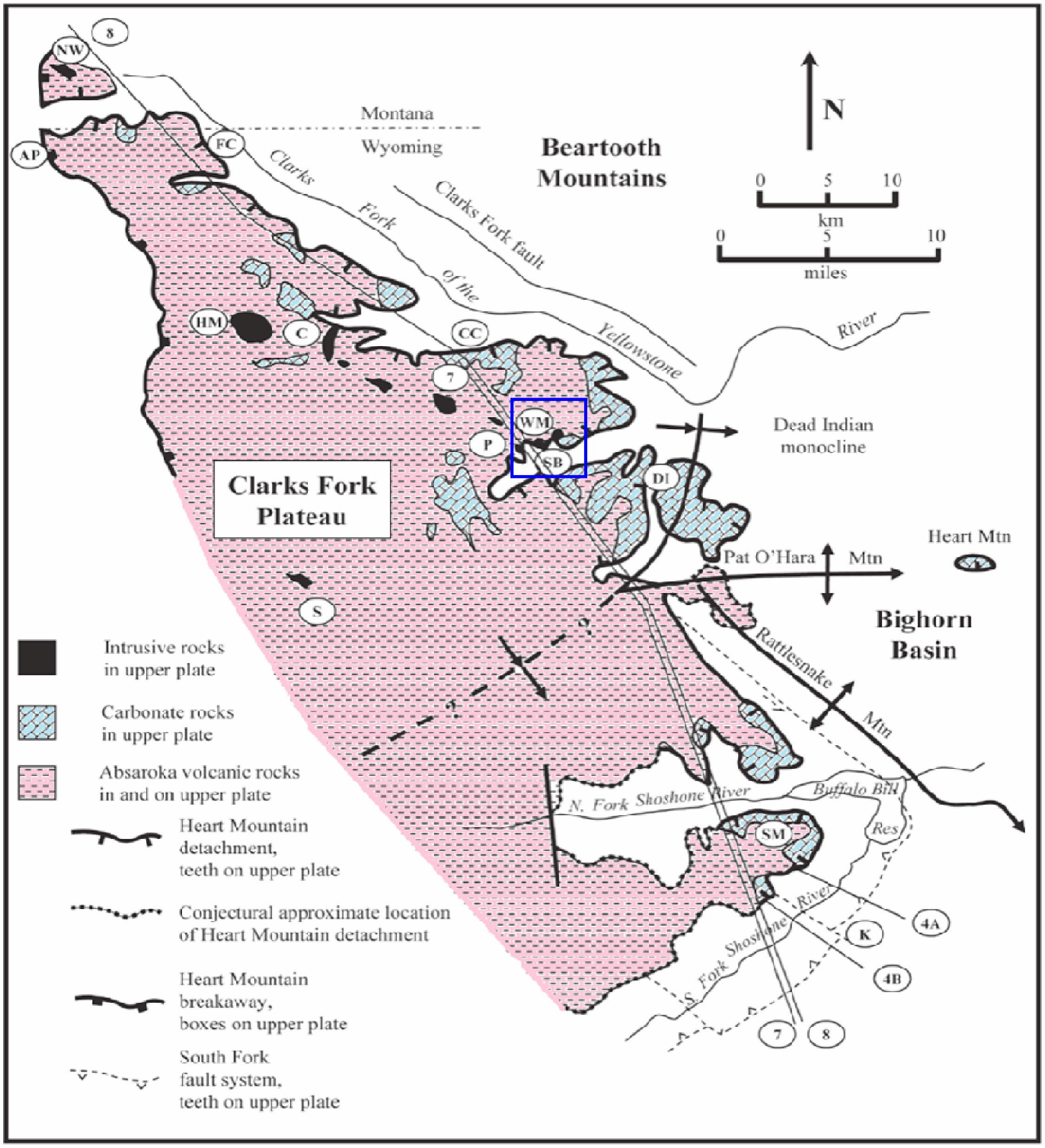

Figure 1. Map of the Heart Mountain detachment. White Mountain identified in blue. Taken from Beutner, 2009.

Formation (Ordovician) (Beutner 2009), and is visible at White Mountain.

White Mountain is an allochthonous block, or a block that has been transported from its source, of upper plate marbleized Madison Limestone Formation (Mississippian), located in Sunlight Basin, Wyoming (Fig. 1) (Craddock et al. 2009). The upper plate rests on approximately 1 meter of fine grained fault breccia made of greater than 80% ground mass and less than 10% country rock now identified as carbonate ultra-cataclasite (CUC) (Craddock et al. 2009). The lower plate consists of Bighorn Dolomite Formation (Ordovician), which has not been altered in anyway (Craddock et al. 2009). Andesitic dikes are oriented perpendicular to the detachment surface and cut across the upper plate, but do not crosscut the lower plate. A variety of CUC termed an injectite (Craddock et al. 2009) is exposed at White Mountain, and is also oriented perpendicular to the detachment surface and extends as much as 30 meters into the upper plate. The term injectite refers to this orientation, which is compared to CUC elsewhere oriented parallel to the detachment surface. Most of the CUC samples are characterized by generally the same bulk geochemistry (Fig. 12). However, one unit originally identified as an injectite--based on preliminary field observations--turned out to have a different geochemistry than the other injectites. This difference in chemistry and heavy mineral assemblage led to the unit being hypothesized as a kimberlite. The purpose of this thesis is to characterize and identify this unit and further constrain the emplacement mechanisms of the HMD.

Kimberlites are ultra-potassic, eruptions originating deep within the Earth's mantle. Kimberlites were originally identified in Kimberly, South Africa and are erupted at speeds exceeding the speed of sound and often contain high temperature/high pressure mineral species such as olivine, clinopyroxene, pyrope garnets, ilmenite, and chromite. Kimberlites often contain diamonds due to the temperature and pressures at which they form which bare economic significance.

White Mountain has been identified as the key to understanding the emplacement mechanisms of the HMD (Craddock, personal communication), due primarily to the presence of the andesitic dikes and CUC injectites. So, a kimberlite not only adds economic implications to the HMD (e.g. the potential to extract diamonds), but could also provide sufficient energy to initiate an event large enough to form the HMD. The goal of this study is to determine whether the unit of study is indeed a kimberlite and further elucidate the implications that this variety of eruption may have had on the emplacement of the HMD.

This thesis is a result of fieldwork completed during the 2011 field season. It builds on projects from the 2010 field season as well. Samples were collected from the unit of study for analysis using polarized light microscopy (PLM), scanning electron microscopy (SEM), Raman microscopy (RM), x-ray fluorescence (XRF) whole rock geochemistry, and U/Pb radiogenic dating using laser ablation multiple collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS). The utility of the analyses is constrained by the quality and amount of sample collected, limitations of the analytical methods, amount of funds available, and the amount of time for analyses.

CHAPTER 2

LITERATURE REVIEW

The Heart Mountain detachment has been studied for over a century. It was originally identified as a thrust (Bucher 1933), but has since been identified as a rootless detachment. Over the years many possible explanations of the mechanisms responsible for emplacement have been presented. Four hypotheses have dominated the modern literature and vary with regards to the mechanisms for emplacement, the rate of emplacement, and the conditions of the upper plate. These hypotheses include a tectonic denudation model, a slow moving continuous allochthon model, a rapid volcanic collapse, and a rapid moving continuous allochthon (Craddock et al. 2009). These different hypotheses will be summarized in generally chronological order.

The Tectonic Denudation Model

Pierce (1957) first presented the tectonic denudation model (Fig. 2) in "Heart Mountain and South Fork detachment thrusts of Wyoming." Tectonic denudation was determined to be synonymous with orogenic erosion (Pierce 1957). Pierce explains that the upper plate was emplaced catastrophically, fracturing the upper plate as it was emplaced across the areal extent of the detachment. These fractures led to denudation of the upper plate prior to deposition of Eocene volcanics preserving the bedding plane of

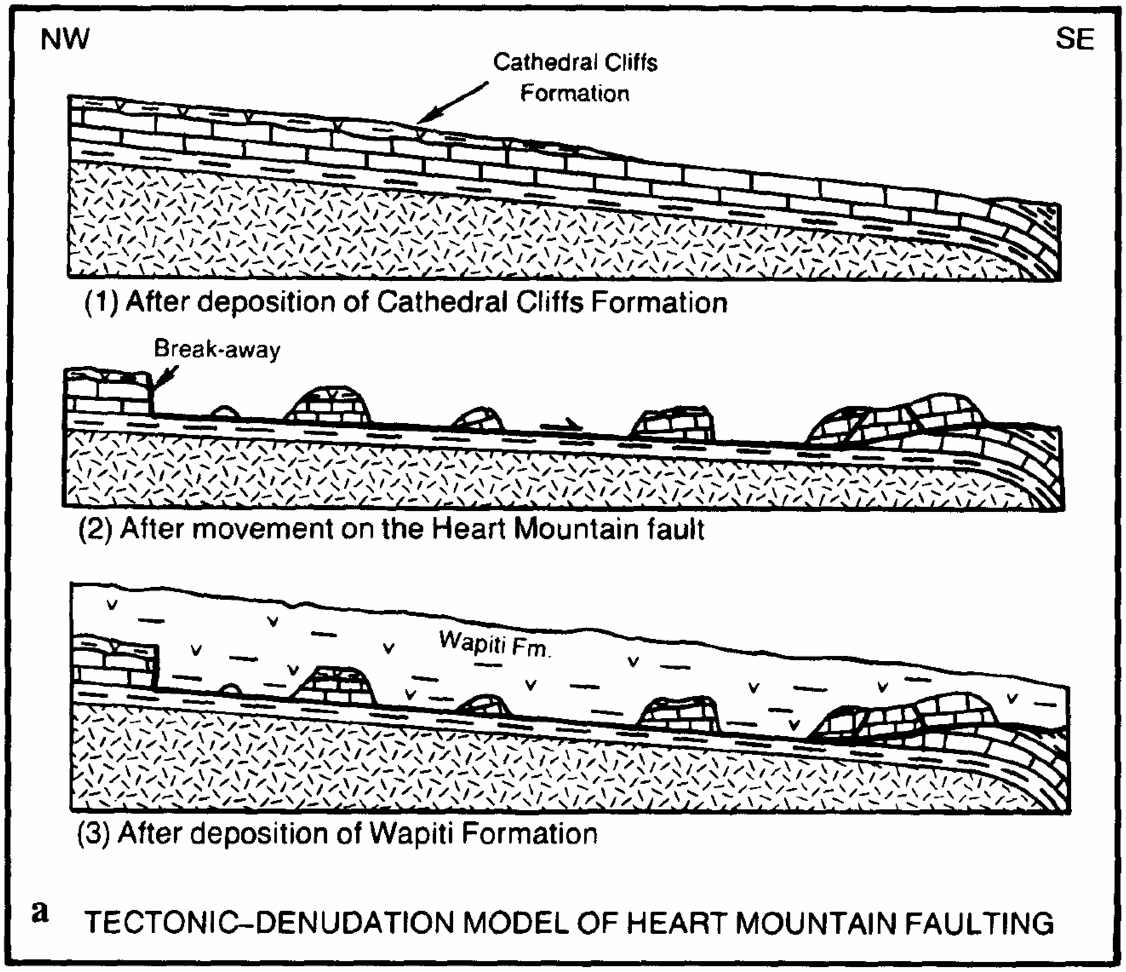

Figure 2. Cartoon of the tectonic denudation model taken from Hauge, 1990.

the detachment. Pierce was the first to identify carbonate fault breccia along the detachment (Pierce 1975). He describes it as having on average greater than 50% matrix made up of fine-grained carbonate matrix. He also describes it as being injected into the upper plate blocks along the detachment as much as 100 feet vertically, yet only retaining thicknesses between 1-24 inches (Pierce 1975). Pierce argues that the emplacement must have been catastrophic, citing evidence that the slope on which the detachment occurred was at most 2°. This indicates that gravity alone could not be responsible for the movement of the upper plate. Also, he cites that the fault occurred in one of the most rigid units of Paleozoic rocks, which would require a significant amount of force. Lastly, he shows that the bedding surface on the lower plate does not show any indication of denudation, which means there was not a sufficient amount of time to erode the surface during or shortly after the emplacement of the upper plate blocks. The root of Pierce's argument resided in his observation that there were no volcanic fragments contained within the fault breccia found along the detachment and the identification and stratigraphy of volcanic units in the area (Pierce 1982).

The Slow-Moving Continuous Allochthon Model

Thomas Hauge first introduced the idea of the continuous allochthon model (Fig. 3) in his paper entitled, "The Heart Mountain detachment fault, northwest Wyoming: Involvement of Absaroka volcanic rock." There are two ways Hauge's model differs with Pierce's tectonic denudation model. The first difference is how Hauge described the upper plate. A "continuous" allochthon describes an upper plate block composed of Paleozoic carbonates and Eocene aged volcanics. Hauge states three sets of field relationships as evidence of a continuous allochthon. First, faults contained within

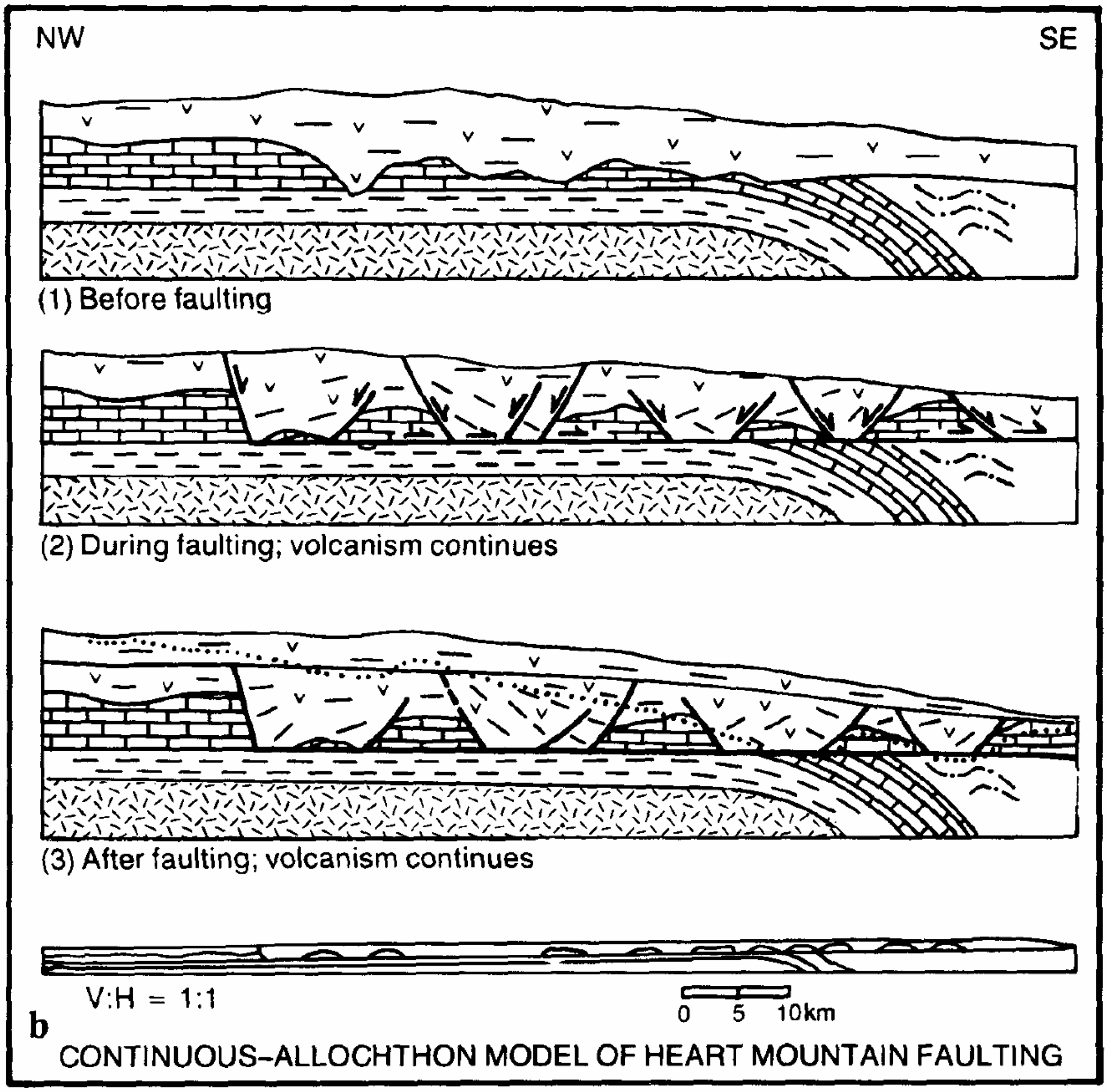

Figure 3. Cartoon of the slow-moving continuous allochthon model taken from Hague, 1990.

volcanic rocks in many areas truncate on the detachment, indicating that the faulting must have occurred at the same time as the detachment (Hauge 1982). Second Hauge observes the presence of volcanic rock clasts contained within the fault breccia along the bedding plane as evidence that the volcanic rocks had to be in place prior to the detachment in order for volcanic material to be included in the fault breccia (Hauge 1982). Lastly Hauge identifies vertical igneous dikes as evidence for the continuous allochthon. He argues the presence of igneous dikes represent the extension that occurred along the upper plate (Hauge 1982). Hauge also argues that by having a continuous allochthon emplaced, it removes the need for a cataclysmic emplacement of the HMD. He explains a continuous allochthon can be emplaced by normal gravity driven processes such as extension and compression (Hauge 1990). In 2009, Hauge revises his original hypothesis and begins to accept the idea of rapid emplacement with fluid pressure reducing friction along the detachment in order to allow the upper plate rocks to move.

Tectonic Denudation vs. Continuous Allochthon

The debate between the tectonic denudation model and continuous allochthon model started with the publishing of the 1982 paper by Bill Pierce and the 1982 paper by Tom Hauge. Both articles were published in the same guide of the same year for a field conference in the vicinity of the HMD. Each article presents conflicting interpretations of the mechanisms of the detachment. The authors present field observations related to Eocene volcanic rocks as evidence for their individual hypotheses.

Despite different ideas about what role the Absaroka volcanics played during the emplacement of the Heart Mountain detachment, both authors realize that the key to understanding the mechanisms lies in understanding the volcanic stratigraphy. Hauge prefers to lump the volcanic units into one large group, not bothering to subdivide them into pre- and post-faulting groups. Pierce however, categorizes the age relationship of the deposited volcanics into pre- (Cathedral Cliffs formation) and post-fault (Wapiti formation). This difference in interpretation is responsible for one major argument between the two authors. Hauge sees the 1000 foot thick Wapiti as being allochthonous and therefore truncated on the fault surface. Hauge also argues there are faults present within the Wapiti that indicate there has been a structural influence to the formation. Conversely, Pierce sees the Wapiti in depositional contact with the fault surface and therefore, not crosscut by the fault. Pierce acknowledges a volume problem and goes on to argue that the original areal extent of the detachment was originally 500 square miles, and then 1300 square miles after the faulting. The area currently covered by the Wapiti formation is much too great to be tectonically emplaced. Therefore the Wapiti must be in depositional contact.

Hauge's hypothesis hinges on the idea that there are volcanics contained within the fault breccia found along the detachment surface. Hauge claims volcanics were found under thin section analysis from samples collected. Pierce argues that there have not been observations of volcanics in a quantity high enough to indicate that the volcanics were in depositional contact with the fault surface during emplacement. Pierce argues that only carbonates from the Paleozoic carbonate units are present, and any presence of volcanics may be explained by upper plate Cathedral Cliffs from tumbling into the breccia during emplacement.

Pilot Peak is another area of disagreement between both authors. There is a unit of steeply dipping volcanic rocks (Cathedral Cliff formation) overlain by two units of volcanics with observable horizontal bedding (Wapiti and Trout Creek Formations). Since Hauge believes that all of the volcanics were deposited prior to the Heart Mountain fault, he believes that the Cathedral Cliffs formation was deposited, followed by the two units with horizontal bedding. Then after all three were in place, the Heart Mountain faulting event occurred. Pierce finds it unlikely that Wapiti and Trout Creek Formations endured the detachment while remaining horizontal. In addition, he argues they are younger than the Heart Mountain detachment itself (Pierce 1982). He therefore argues the following scenario. The Cathedral Cliffs formation was deposited and faulted, causing it to be steeply dipping. Next the detachment occurred, and then shortly after, the younger Wapiti and Trout Creek formations were emplaced.

One area that both authors agree on is that if tectonic denudation had occurred, then the relative amount of time that the surface was exposed to erosive forces must have been brief. Hauge cites the lack of evidence of subaerial weathering on the surface of the lower-plate. Pierce agrees, and insists that emplacement of the upper-plate must have been catastrophic in nature in order to limit the amount of time the lower plate would have been exposed to the elements. Pierce further argues that the lower plate was protected by penecontemporaneous deposition of the volcanics after the emplacement of the detachment. Hauge agrees that if the surface was exposed it must have been exposed briefly. However, he does not support the notion of cataclysmic emplacement, instead he argues that the lower plate was never exposed to denudation due to the presence of volcanic rocks in the continuous allochthon.

Both articles describe the role of the Absaroka volcanics played in the emplacement of the Heart Mountain detachment. The root of disagreement between both authors centers on the volcanic stratigraphy of the area. Differing observations have been made by both authors with regards to the presence of volcanics in fault breccia, as well as the rate of emplacement for the detachment. Each author uses conflicting field observations to garner support for their own hypotheses, but emphasizes the importance of the volcanics in their reasoning.

These articles are followed by several follow-ups and responses. Pierce is the first to respond with a paper reiterating similar evidence as mentioned in his 1982 paper in addition to several lines of new evidence. He argues that stream-channels that have down cut into the tectonically denuded surface have been off-set by the HMD, fault breccia penetrate overlying Wapiti formation and contain xenoliths and wood phenoclasts indicating surficial exposure, Wapiti rocks exhibit chilled borders when in contact with Paleozoic rocks, and faults contained within the upper-plate do no penetrate the Wapiti (Pierce 1987).

Three years later in 1990, Hauge responds to Pierce's arguments with a paper entitled "Kinematic model of a continuous Heart Mountain allochthon." One by one Hauge produces counter arguments against those put for by Pierce.

The back and forth between Hauge and Pierce ended when Pierce retired. However, there was still much controversy over the mechanisms of emplacement of the HMD.

Volcanic Collapse Model

Dave Malone is credited with advocating the volcanic collapse model (Fig. 4). The eruption of Mt. St. Helens shifted the paradigm of understanding surrounding the collapse of volcanic complexes as a result of a lateral blast (Malone 1995). The author

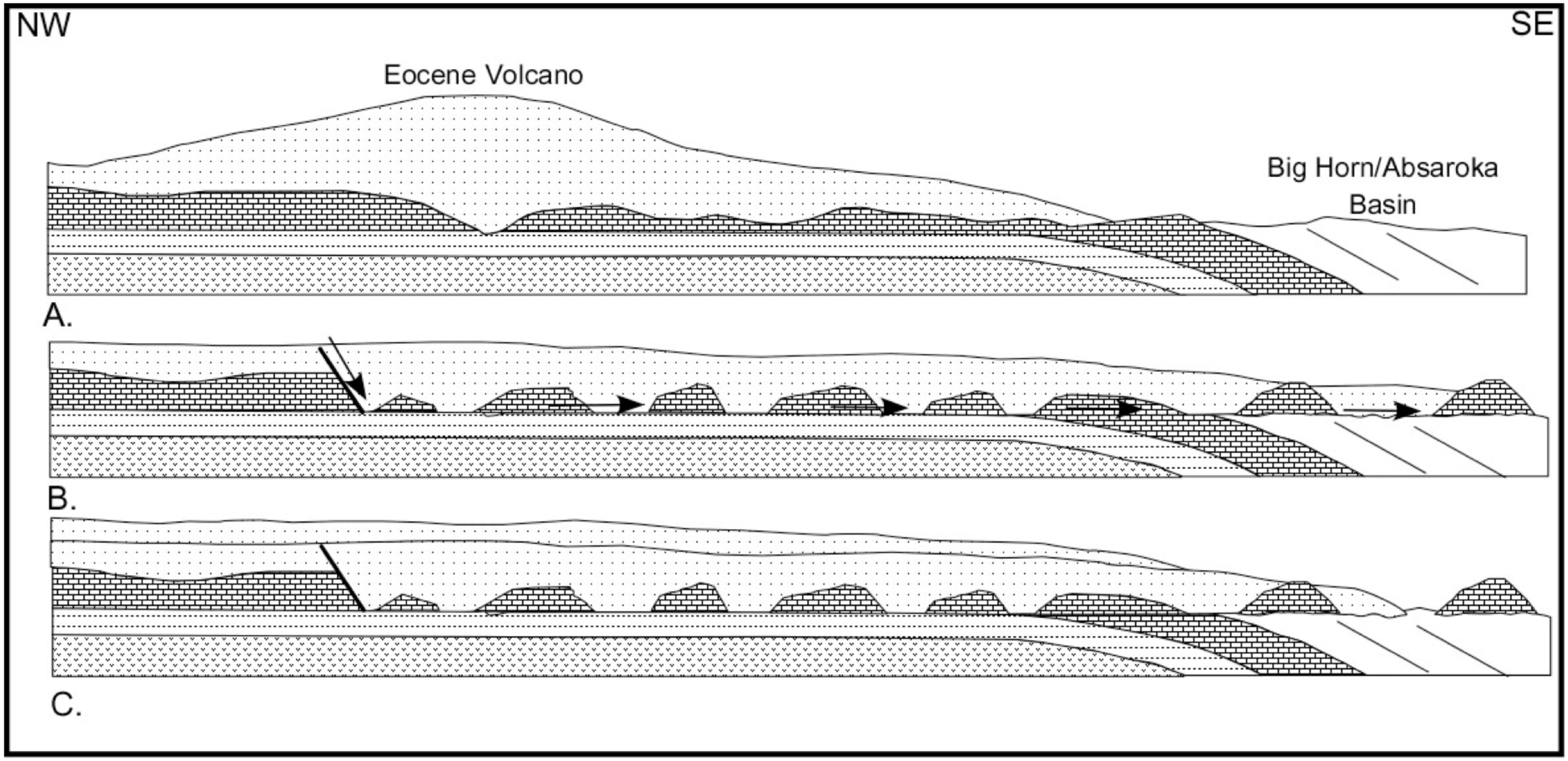

Figure 4. Cartoon illustrating the collapse of an ancestral volcanic complex taken from Malone, 2008.

describes the Deer Creek member of the Wapiti formation, which has been characterized as a lahar deposit and is contemporary to the emplacement of the HMD (Malone 1995). The growth of volcanic complexes reduced slope stability, and then with an influx of volcanic gases, normal stress was reduced, initiating the detachment (Malone 1996). The frictional heating resulted in the dissociation of CO_2 leaving behind the fault breccia (Malone 1996). The emplacement of the detachment resulted in blocked paleodrainages evidenced by detrital zircon studies (Malone 1996). The development of the volcanic collapse model is what developed into the currently accepted hypothesis of a rapid moving continuous allochthon.

Rapid-Moving Continuous Allochthon Model

After collaborating with Tom Hauge, Ed Beutner published his 2005 paper, "Catastrophic emplacement of the Heart Mountain block slide, Wyoming and Montana, USA", which suggested a rapid-moving continuous allochthon (Fig. 5). The root of the new argument is supported by evidence of glassy accreted grains within the fault breccia at the base of the detachment, presence of sedimentary structures within the fault breccia, and the lack of deformation along the lower plate (Beutner 2005). Aided by a fluid primarily of supercritical CO_2 and water (Beutner 2005), the upper plate glided down the low angle fault surface much like a hovercraft. Source for the CO_2 is suggested as volatilizing of carbonate due to frictional heating (Beutner 2005). A hypothesized impetus for emplacement has been described as a lateral volcanic eruption of the Crandall, New World, or Sunlight volcanic centers (Beutner 2005). Movement along the

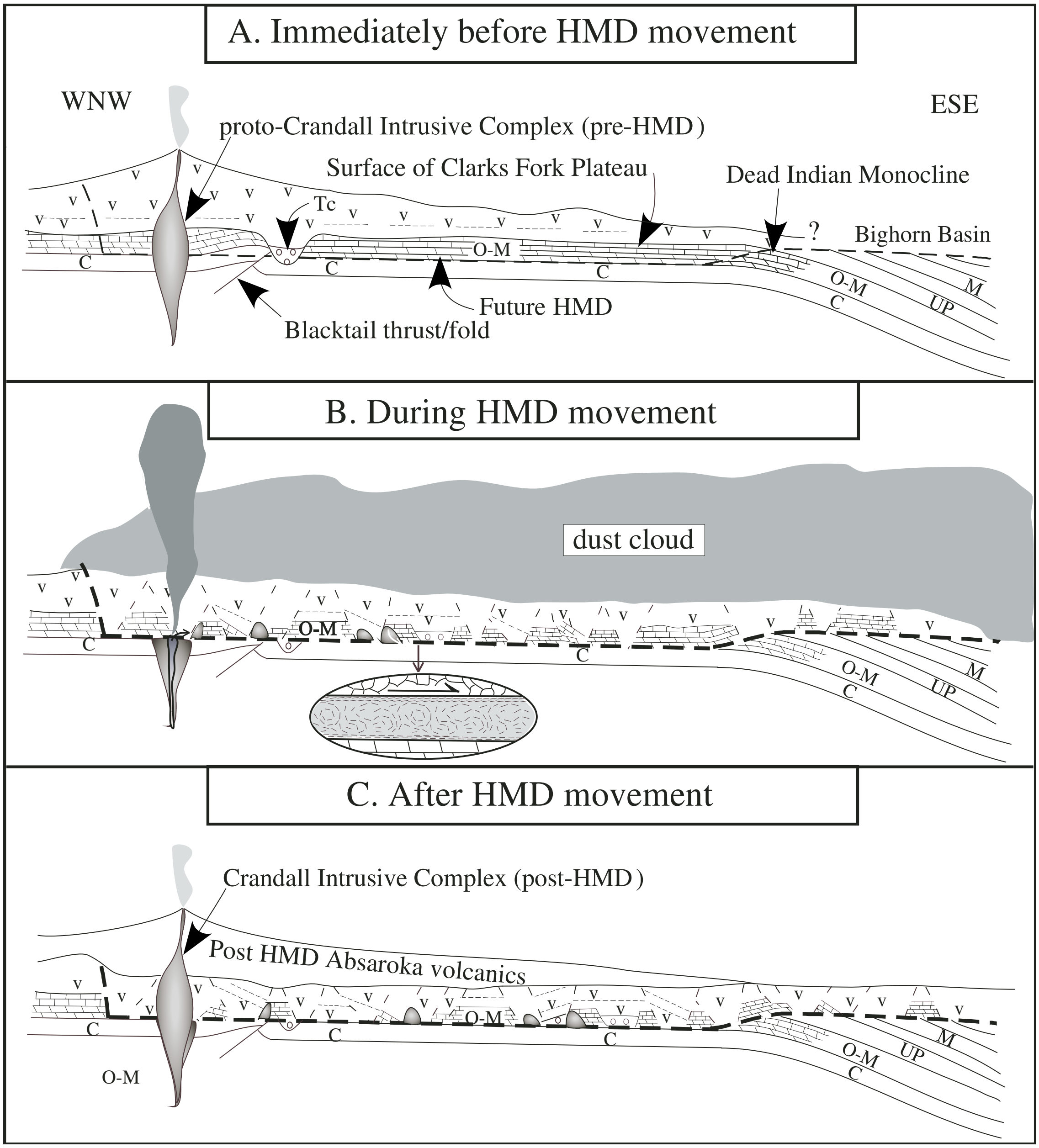

Figure 5. Cartoon of the rapid-moving continuous allochthon model taken from Beutner, 2005.

detachment would have continued except for the occasional contact between the upper plate and lower plate where moderate deformation has been observed in the lower plate (Beutner 2005).

In 2009, Craddock et al. elaborated on this hypothesis with new evidence. Observations were made regarding calcite twinning strain analysis, anisotropy of magnetic susceptibility (AMS), XRF, and SEM using energy-dispersive spectrometry (EDS) (Craddock et al. 2009). Results indicate stresses between -34 to -39 MPa of differential stress between the upper and lower plate block indicating there was less strain on the lower plate (Craddock et al. 2009). Also AMS indicated a flattening direction parallel to the plane of the detachment (Craddock et al. 2009). Lastly, XRF analysis shows that the CUC injectite material is very different geochemically from the surrounding carbonate rocks, yet different injectites maintain similar geochemical compositions (Craddock et al. 2009).

Conclusions of this paper show support for Crandall volcanics related to the emplacement of White Mountain—an HMD allochthon. The detachment occurred as the flank of these volcanic centers expanded/inflated increased the angle of dip of the proto detachment surface, as a result of a volcanic eruption, degassing of the CO_2 occurred, causing an emplacement rate of 126-340m/s for the entire structure, which is supported by observations made at White Mountain (Craddock et al. 2009).

CHAPTER 3

METHODS

Samples were collected during the 2011 summer field season and prepped for analysis at Macalester College in St. Paul, Minnesota. Five samples (#11-K-1 through 6) of the originally identified kimberlite body were collected along the length of the unit on the western-most ridge of White Mountain (Fig. 6). Additional samples were collected from other andesitic dikes (#11-A-1 through 5) and CUC injectites (#CUC-1, 5, and 8) on White Mountain.

The samples from White Mountain were first cut into 22 thin section billets. Remaining sample material was powdered using a Tungsten Carbide shatterbox, which was thoroughly cleaned after each sample in order to reduce the possibility of contamination during major and trace geochemical analysis. Powders were then sent to University of Wisconsin at Eau-Claire for complete major and trace elemental analysis, using XRF. Thin sections were analyzed using polarized light microscopy (PLM) at Western Kentucky University. The remainder of sample 11-K-5 was crushed and separated into zircon mineral splits using a Wilfley table, magnetic separation, and heavy liquids for analysis of U-Pb dates at the LaserChron Lab at the University of Arizona.

Figure 6. A view of White Mountain facing north.

CHAPTER 4

RESULTS AND DISCUSSION

Kimberlites originate in the mantle and are erupted to the surface at speeds exceeding the speed of sound. The usual surficial expression is characterized by the presence of blue powder. The deeper facies includes brecciated rock, with angular clasts that increase in size with depth. If the hypothesized kimberlite is indeed a kimberlite, it will most likely be exhibiting this brecciated texture.

The hypothesized kimberlite was exposed in one large outcrop approximately 30 meters by 6 meters in lateral extent. The outcrops were highly heterogeneous, being composed of clasts of different lithologies in a generally fine-grained groundmass. Clast lithologies are dominated by andesite and pyroxenite (igneous) and marble (metamorphic) types. No reaction rims were observed around the clasts, which were primarily angular in aspect and contained within a white groundmass (Fig. 7). Macroscopic mixing textures were also present (Fig. 8). This heterogeneity and the angularity of the clasts are certainly consistent with models supporting high-energy emplacement.

Complete whole rock geochemical analyses are shown in Table 1 and Table 2. Concentrations of several elements have considerable ranges for the kimberlite samples

Figure 7. Hypothesized kimberlite in outcrop. Clasts of pyroxenite contained within a plagioclase feldspar dominated groundmass. Acid bottle for scale.

Figure 8. Macroscopic mixture textures present in the hypothesized kimberlite in outcrop. Ring for scale.

Major Element Composition											
Sample	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	Total
11-K-1	57.41	0.82	13.89	5.97	0.10	4.42	7.20	0.93	8.64	0.62	100.00
11-K-2	43.05	0.51	10.74	4.91	0.00	14.21	25.56	0.10	0.72	0.20	100.00
11-K-3	48.28	1.66	15.71	10.93	0.10	5.72	9.37	1.66	5.10	1.46	100.00
11-K-4	52.89	0.93	19.73	7.44	0.10	4.44	6.40	3.51	3.82	0.72	100.00
11-K-5	48.78	0.85	14.21	6.47	0.10	6.15	18.45	1.91	2.23	0.85	100.00
10-K-1	43.30	0.74	14.45	6.10	0.09	9.83	23.04	1.32	0.46	0.66	100.00
10-K-2	45.71	0.84	14.21	8.28	0.11	7.42	18.55	1.96	2.09	0.83	100.00
CUC-1	49.58	0.84	14.98	6.12	0.10	5.80	16.98	2.32	2.53	0.74	100.00
CUC-5	14.52	0.14	1.78	1.10	0.00	21.23	60.68	0.14	0.27	0.14	100.00
CUC-8	22.87	0.13	4.65	1.68	0.00	17.57	52.71	0.13	0.13	0.13	100.00
11-A-1	55.72	0.84	17.84	7.03	0.10	4.20	3.78	2.94	7.03	0.52	100.00
11-A-2	56.05	0.94	17.43	7.83	0.10	4.38	6.26	3.97	2.61	0.42	100.00
11-A-3	53.12	0.74	16.61	7.20	0.10	5.82	9.63	3.07	3.28	0.42	100.00
11-A-4	63.64	0.52	17.24	5.33	0.10	2.93	4.08	3.03	2.93	0.21	100.00
11-A-5	54.95	0.84	15.79	8.21	0.10	8.42	5.79	2.95	2.63	0.32	100.00

Table 1. Major element composition from XRF analysis in weight %. Results are normalized to 100% for comparison. Hypothesized kimberlite samples are in red, CUC samples in purple, and igneous samples are in green.

Trace Element Composition																		
Sample	**Nb**	**Zr**	**Sr**	**Zn**	**Ni**	**Cr**	**V**	**Ce**	**Ba**	**La**	**Y**	**Rb**	**Th**	**Pb**	**Sc**	**Co**	**Nd**	**Hf**
11-K-1	6	210	1220	54	40	67	112	84	1874	47	8	104	4	16	11	24	31	3
11-K-2	6	95	150	35	33	52	68	45	602	19	21	20	4	7	19	15	22	2
11-K-3	14	187	1178	73	39	88	219	167	1652	91	16	82	3	16	15	33	62	2
11-K-4	14	258	1641	64	58	127	114	96	1452	50	9	102	8	18	8	28	31	3
11-K-5	12	267	1313	61	40	62	112	97	1009	52	21	46	8	18	17	22	38	4
10-K-1	Na	Na	Na	25	38	103	112	86	1192	Na	Na	Na	Na	Na	11	18	Na	Na
10-K-2	Na	Na	Na	47	86	215	131	104	1316	Na	Na	Na	Na	Na	7	32	Na	Na
CUC-1	13	298	1147	62	38	47	108	100	939	53	23	54	9	27	15	19	35	6
CUC-5	1	23	137	14	3	0	10	0	43	0	7	8	2	6	22	3	9	0
CUC-8	1	37	210	21	8	0	25	21	54	4	9	5	1	7	21	3	11	0
11-A-1	11	220	1038	45	21	26	122	99	1537	57	8	133	8	19	10	23	32	4
11-A-2	7	197	929	68	50	65	175	86	1274	46	15	51	5	10	15	30	40	3
11-A-3	8	204	1154	64	25	38	131	83	1566	51	15	64	6	15	14	23	33	3
11-A-4	6	187	775	76	15	93	90	65	1641	37	19	51	5	17	10	20	26	4
11-A-5	4	148	809	69	80	204	175	44	1113	26	16	37	2	11	21	37	23	2

Table 2. Trace element compositions from XRF analysis in ppm. Hypothesized kimberlite samples are in red, CUC samples in purple, and igneous samples are in green.

such as: 42-57% SiO_2, 11-19% Al_2O_3, 5-11% Fe_2O_3, 6-25% CaO, 4-14% MgO, and 150-1641 ppm Sr. The igneous samples fall generally within the range of basalt to andesites. This is consistent with the andesitic compositions present in the Absaroka Range, in which the HMD is located.

In order to determine whether or not the hypothesized kimberlites were indeed kimberlites, the whole rock geochemical results were compared to ~1100 publishedwhole rock kimberlite geochemical results found in the GEOROC database. Plots show large differences between data analyzed for this project and the published data (Fig. 9). For example, there is a wider range in analyzed potassium (K) concentrations (0.46 - 8.64 wt%) than the range in published kimberlites, which are identified as generally ultra-potassic. The kimberlitic samples from this project also show enrichment in calcium (Ca) greater than the published kimberlitic trend. These data suggest that the hypothesized kimberlites are not similar geochemically to what is currently considered accepted kimberlite compositions. Moreover, it should be noted that the range in White Mountain samples represents the range of compositions in one unit, and not a wide variety of kimberlitic locales.

Multi-element diagrams (“spider diagrams”) are useful for comparing unknown (sample) whole rock compositions to known standards, and for assessing relative concentrations of a variety of elements. The Pearce (1983) MORB spider diagram lists Large Ion Lithophile Elements (LILE) first with increasing incompatibility from left to right, followed by High Field Strength Elements (HFSE) with increasing incompatibility from right to left. These diagrams may be used to show the range in elemental abundances for a number of samples on the same plot.

When plotted on a Pearce (1983) spider diagram comparing samples (unknowns) to mid-ocean ridge basalts (MORB), the kimberlitic samples are very similar to one another, except for sample 11-K-2 (Fig. 10). When the average kimberlitic composition, from samples 11-K-1 through 11-K-5, is plotted against the average igneous composition, from samples 11-A-1 through 11-A-5, both units are strongly similar (Fig.11). This strong relationship demonstrates that the igneous units and

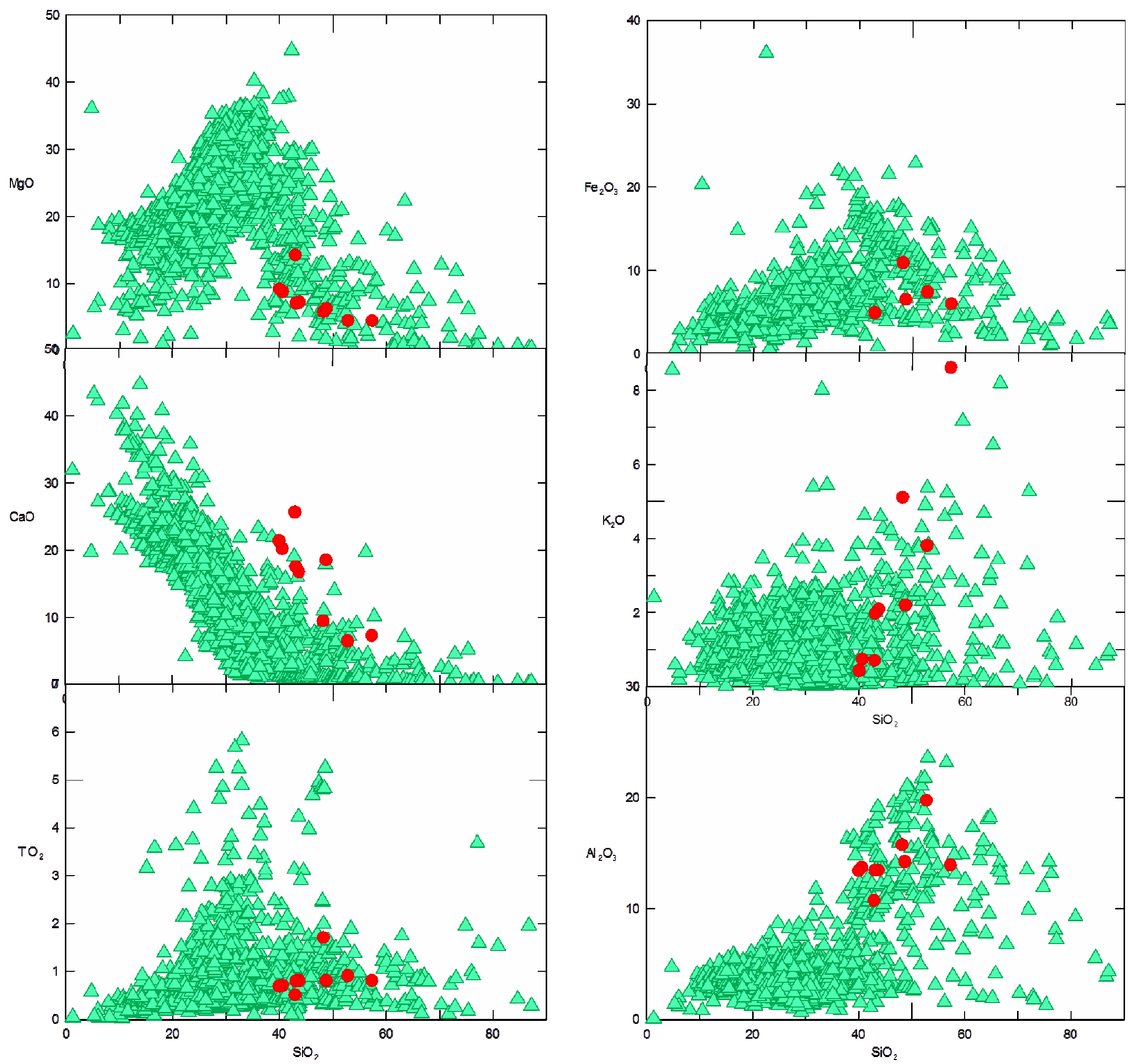

Figure 9. Kimberlite samples compared to whole rock geochemical results of published kimberlites from GEOROC database.

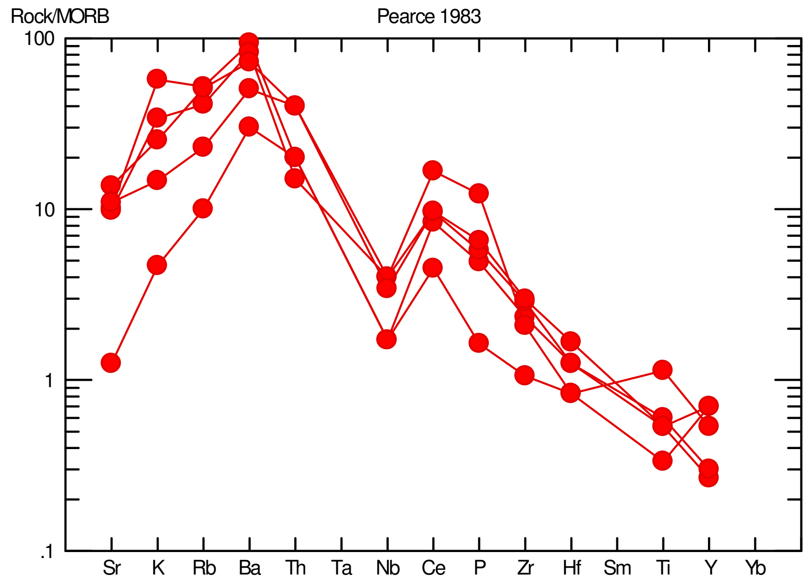

Figure 10. A. Pearce (1983) spider diagram for kimberlite samples.

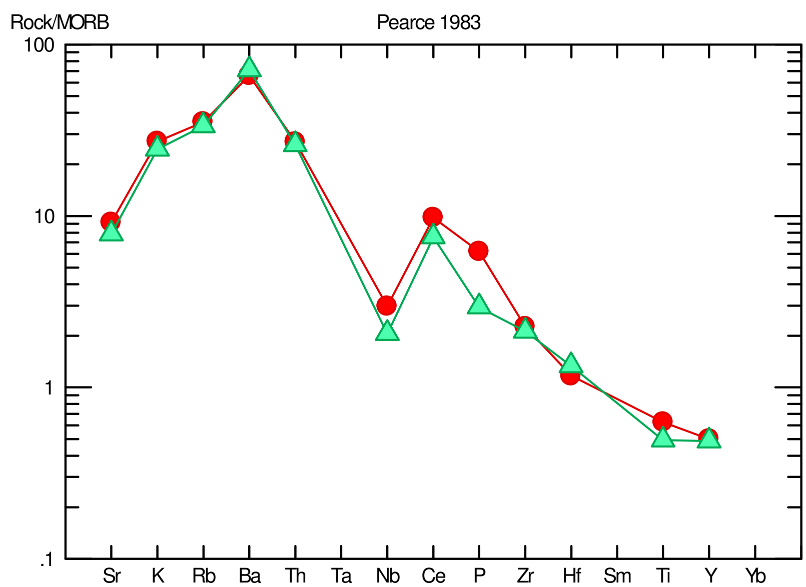

Figure 11. Pearce (1983) spider diagram comparing average kimberlite sample (red) compared to average igneous composition (green). hypothesized kimberlites are geochemically the same, and probably from the same source.

and hypothesized kimberlites are geochemically the same, and probably from the same source.

There is high level of geochemical variation in the CUC analyses, and one CUC analysis is far more similar to the hypothesized kimberlite samples than to the other CUC units. CUC injectites collected in 2009 have been described as being geochemically identical (Craddock et al. 2009), while this year's CUC samples exhibit a greater range in compositions (Fig. 12). This suggests far more compositional variability in the CUC injectites than originally thought. The average composition of CUC analyses is compared to the average hypothesized kimberlite composition and igneous compositions in Figure 13, and is demonstrably different. Furthermore, the diagram shows that mixing between igneous and CUC rock types is not responsible for producing kimberlitic compositions.

XRF analyses of hypothesized kimberlite samples exhibit a number of inconsistencies, which is possible evidence of contamination. Both the hypothesized kimberlite and CUC units are brecciated. Because the entire rock is powdered in preparation for XRF analysis, compositions of different clasts contained within a rock can influence the whole rock geochemistry. Consequently there exists some doubt about the reliability of XRF results, since the clasts were not separated from the groundmass prior to XRF analysis.

Analysis using PLM shows kimberlitic samples contain lithic clasts within a plagioclase-rich matrix. Three dominant rock types present as clasts include pyroxenite, marble, and porphyritic andesite. A mortar texture is also present around clasts,

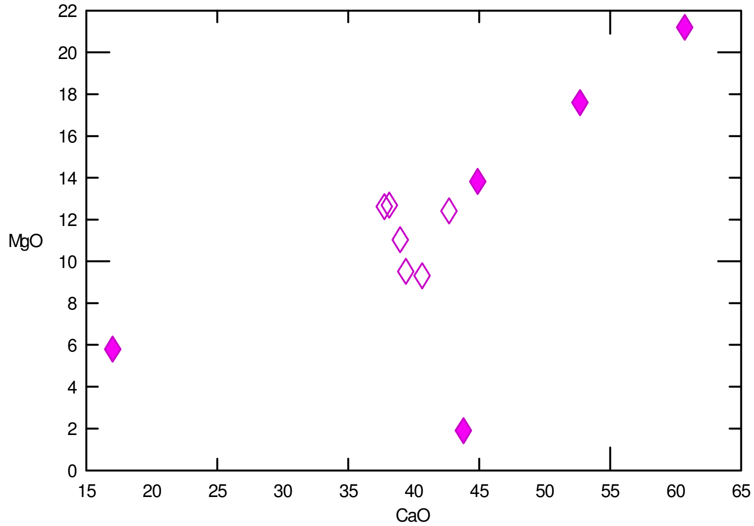

Figure 12. CUC samples compared using CaO and MgO. Filled symbols are analyses from 2011, hollow symbols are from Craddock et al. 2009.

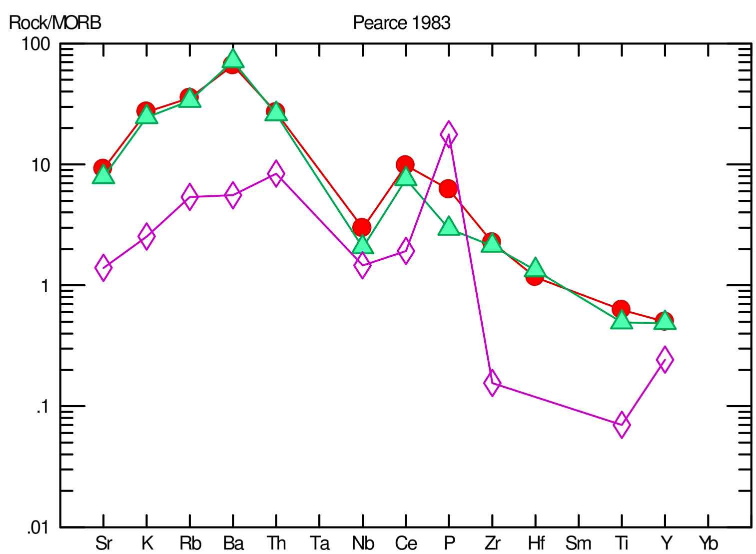

Figure 13. Pearce 1983 spider diagram comparing average geochemical results of hypothesized kimberlite samples (red), igneous samples (green), and CUC samples (purple).

particularly the pyroxenite (Fig. 14). A distinct foliation is noticeable around some clasts in thin section (Fig. 15). A number of clasts contained generally euhedral apatite crystals, of unknown origin at this point (Fig. 16). Minerals present include, clinopyroxene, plagioclase feldspar, biotite, hornblende, garnet, spinel, zircon, and apatite.

These textures indicate a tectonically altered rock. Mortar textures indicate that this rock was involved in a cataclastic flow. The presence of thomsonite veins shows the rock has been fractured and then thomsonite filled the fracture after their formation. The apatite and tremolite crystals point to metamorphism since tremolite does not occur as a primary igneous mineral. All evidence points to this rock being altered dramatically after the unit crystallized.

Radiometric dates (U/Pb) from zircons from sample 11-K-5 and igneous samples show an age of 48.9 mya (+/- 1.2 mya). This age is consistent with accepted ages for the HMD. The age being consistent points to the elevated role of igneous activity at the time of the HMD's emplacement.

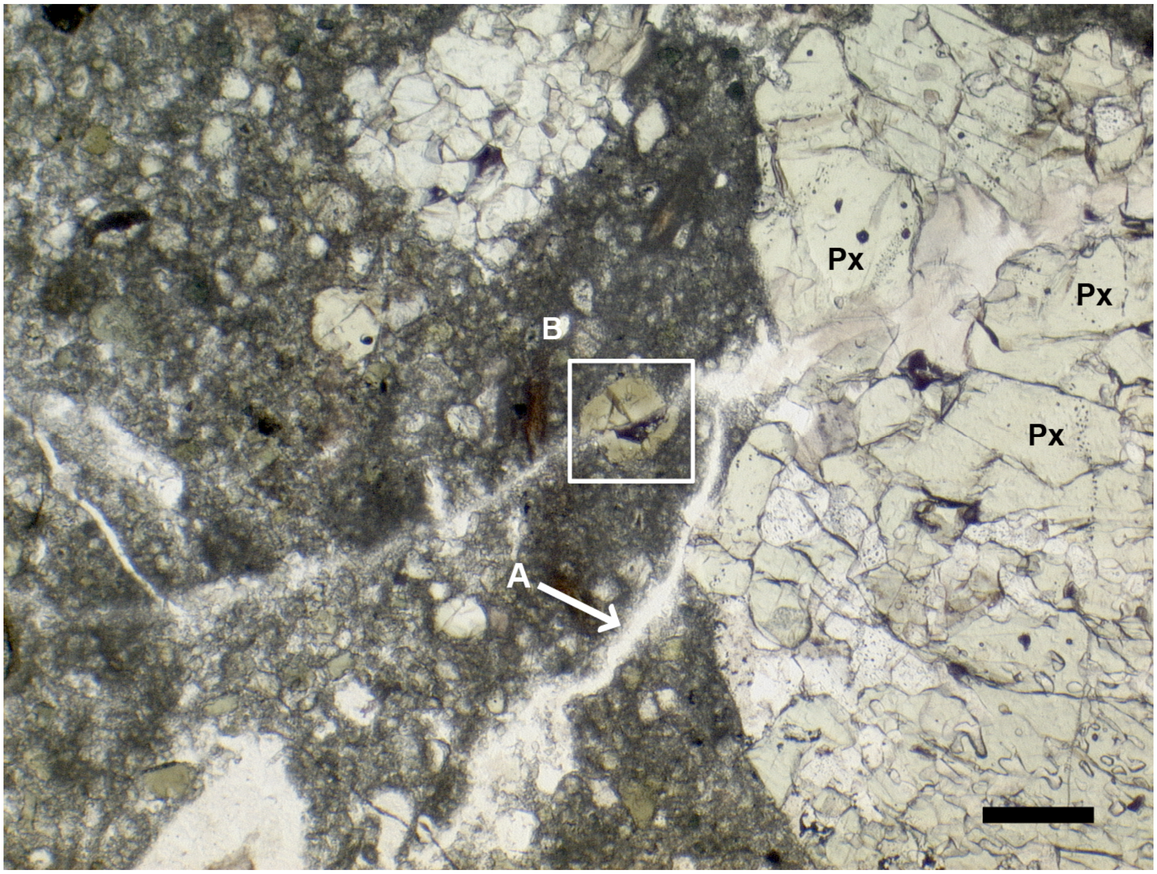

Figure 14. Photomicrograph taken from sample 11-K-5 in plane polarized light. Secondary thomsonite fills fractures as veins (A). Pyroxenite (Px) clast exhibits mortar texture (B). Scale is equal to 200 μm.

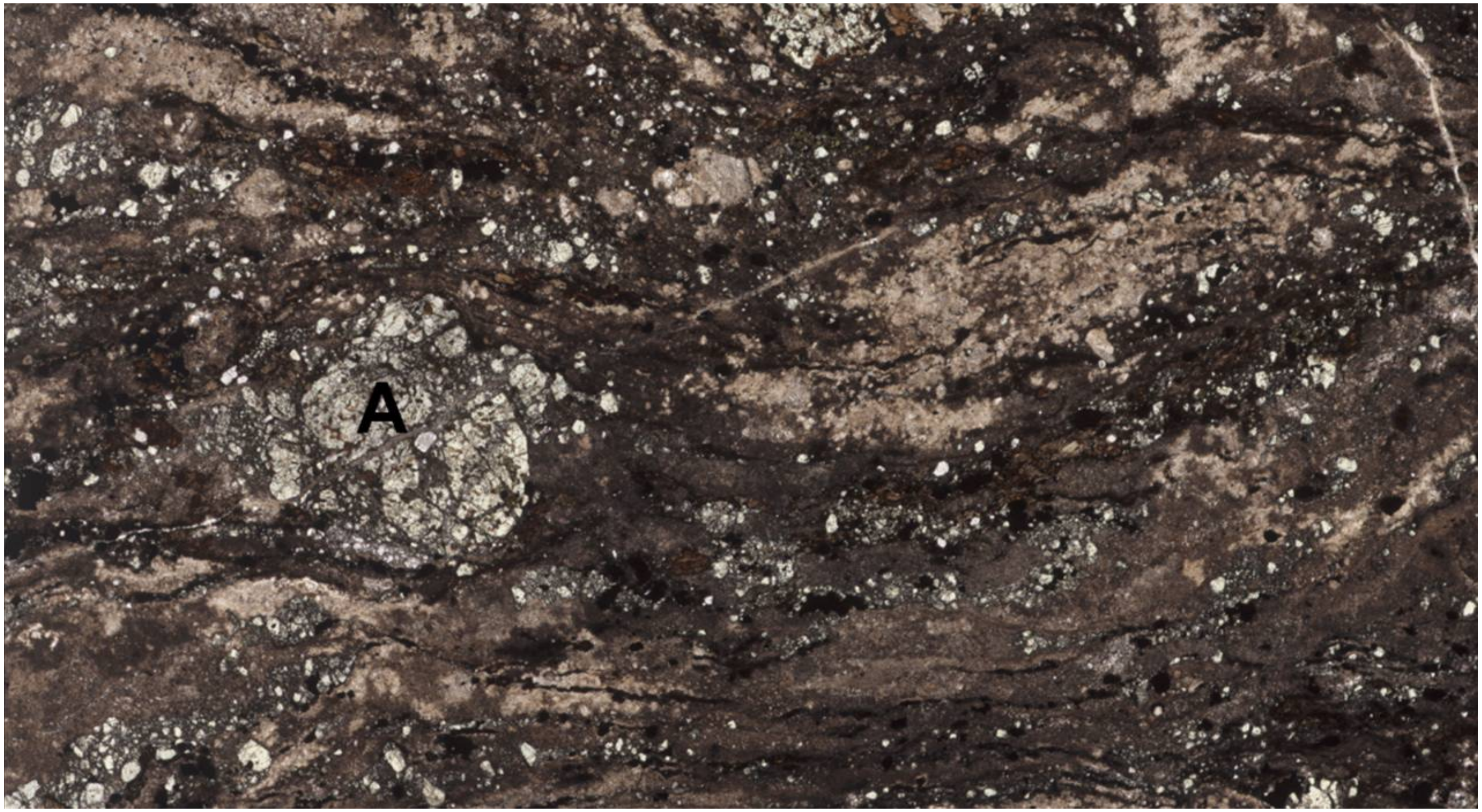

Figure 15. Transmitted light scan of thin section 19 sample 11-K-5. Foliated texture visible around a pyroxenite clast (A).

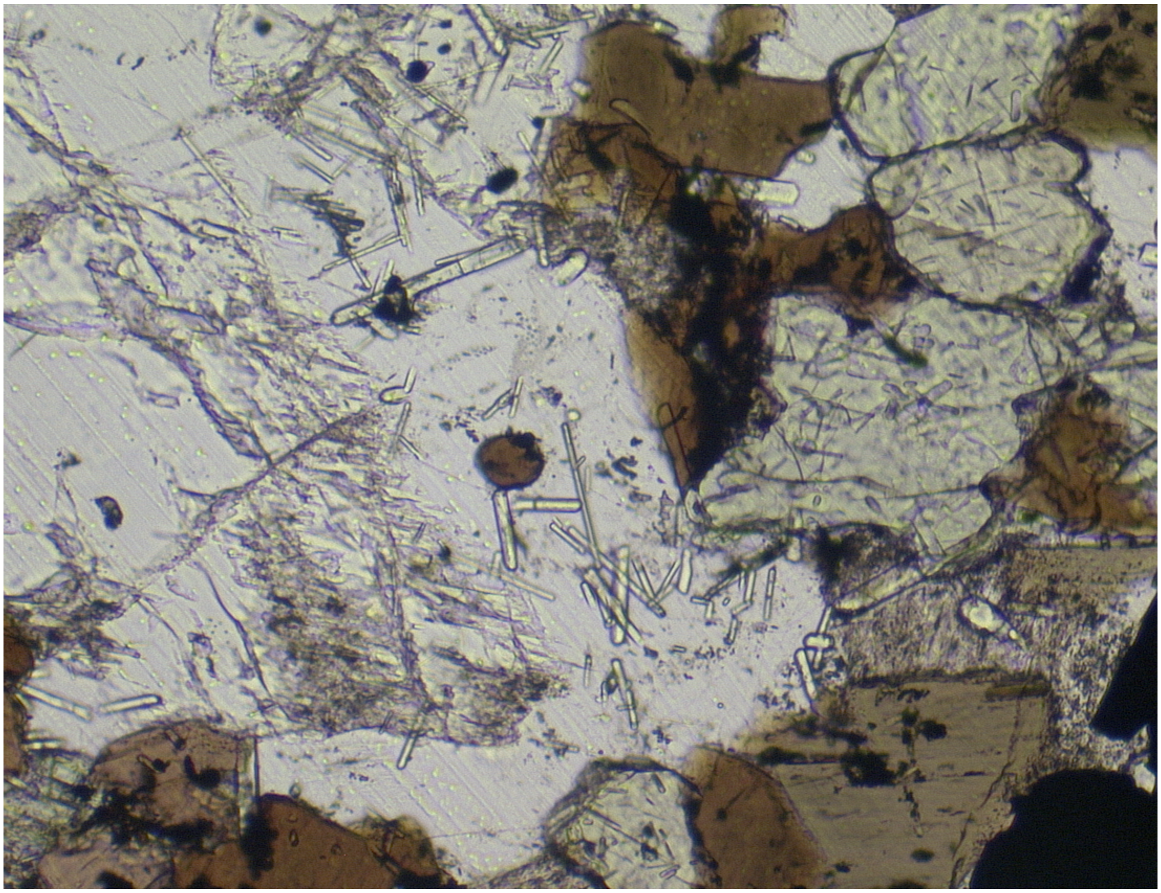

Figure 16. Transmitted light microscope image under 30 x objectives on the Raman Microscope. Apatite crystals contained within the groundmass of the unit.

CHAPTER 5

CONCLUSION

The hypothesized kimberlite was mistaken for CUC injectite during field work in 2010. Geochemistry results indicated that this unit was extremely different from the CUC warranting further investigation. It was originally hypothesized as kimberlite based on its heavy mineral assemblage including, olivine, spinel, and garnets. This in conjunction with elevated Chromium (Cr), pointed to a potential kimberlite.

After comparing the unit to 1100 published kimberlite whole rock geochemical results, it is obvious this unit is not similar to accepted kimberlite compositions. It is instead the same geochemically as the andesitic dikes that also occur on White Mountain. This is unexpected since this unit exhibits extremely different textures in the field and in thin section analysis as compared to the andesites.

Geochemical results for CUC samples also show that perhaps the homogeneity of the injectites is not as certain as originally stated by Craddock et al. 2009.

The radiogenic dates from zircons extracted from the hypothesized kimberlite indicate that these units are within the accepted age ranges of the HMD, which shows an elevated level of igneous activity at the time of emplacement.

Future work would include further geochemical analysis of the unit with an emphasis on the groundmass rather than whole rock geochemistry. Also, XRD analysis could further constrain the mineralogy of the groundmass and clasts. Apatite fission tracking could provide insight into the cooling date of the unit, or could also be used for additional radiogenic dates.

APPENDIX A

KIMBERLITE

Kimberlites typically contain diamonds due to the mantle pressures and temperatures from which they originate. Additional analysis of specific mineral phases in thin sections using RM indicates the presence of diamonds in several samples and in several distinct mineral phases. The presence of diamonds, in addition to the mineralogy, would be strong evidence that the unit is indeed of kimberlitic origins.

Most of the diamond occurrences appear to be aggregates of many fine (<5 µm) diamond crystals and are pink in color. The diamonds have been observed on the surface of the slides primarily along linear features such as cracks and mineral grain boundaries. The diamonds also occur in association with several different mineral species including analcime, augite, thomsonite, and one currently unidentified mineral species. The majority of the diamond crystals have been observed on the surface of the polished thin sections, and some appear to be contained within minerals, through analysis using both PLM and reflected light microscopy.

The kimberlite argument is supported if these diamonds occur as primary minerals along with the clinopyroxenes and other observed mantle-derived minerals.

However, there are still some doubts with regards to the origins of diamonds. For example, the diamonds could have been introduced to the thin sections during the process of polishing (using diamond paste) for microprobe use. The lab responsible for the preparation of the thin sections was contacted and it was determined that the diamond crystals contained within the paste are less than 0.5 µm. The slides also contain extra feldspar fragments around the outside of the billet to help the lab gauge the thickness of the thin section as it was being prepared. Diamonds exhibiting a similar shape and color have been observed around these extra feldspar fragments indicating contamination. Photomicrographs were also sent to the lab responsible for the slides' preparation, but it was their opinion that the diamonds were not a result of contamination.

Some diamonds did not exhibit the aggregate texture that was observed. Instead, these diamonds occurred in association with clinopyroxene and appeared to be single grains (Fig 17). These diamonds also appeared pink in reflected light and the Raman signals used to identify the minerals were different than the signals of the aggregate diamonds. This evidence suggests these diamonds are primary, and not the result of contamination, and therefore the unit is likely of kimberlitic origins.

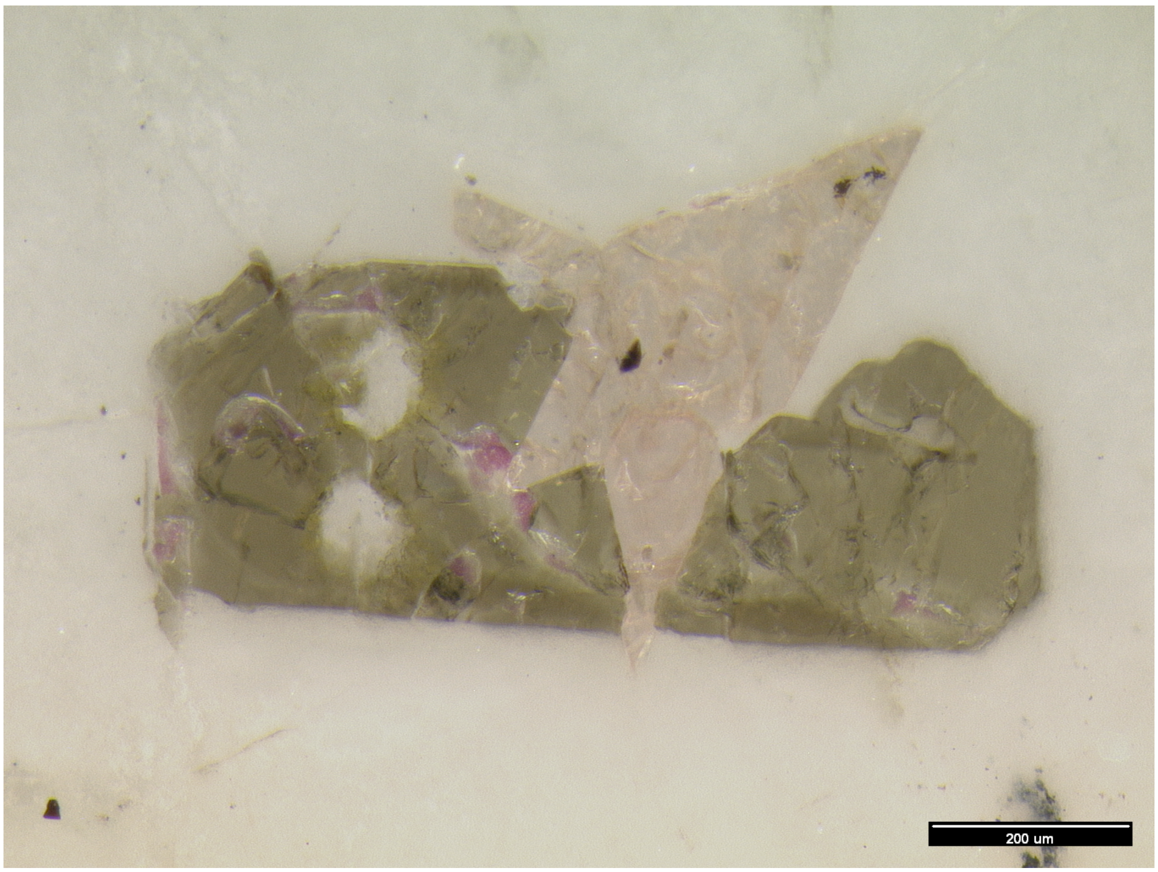

Figure 17. Clinopyroxene grain contained within analcime with pink diamond inclusions.

APPENDIX B

SKARN

The mineral assemblage of clinopyroxene + garnet + olivines + spinel is not restricted to kimberlites. Similar mineral assemblages have been identified in association with contact metamorphosed carbonates, or skarn, in various locations. A skarn is a calc-silicate rock derived from the contact metamorphism between a carbonate country rock, and a silicate intrusive rock. The primary difference is the presence of demonstrably metamorphic minerals in these assemblages. For example, a pyroxenoid such as wollastonite is typically associated with metamorphic environments, and is not found in igneous assemblages.

Wollastonite fibers were identified in heavy splits extracted from powders of samples of the hypothesized kimberlite. The presence of wollastonite (pyroxenoid), augite, diopside (clinopyroxenes), and garnet are similar to mineral assemblages of skarns identified in Crestmore, California and the Adirondack Mountains, New York. The Crestmore skarns contain olivine (forsterite, monticellite, merwinite), clinopyroxene (Diopside), pyroxenoid (wollastonite), vesuvianite, and garnet. The Adirondack skarns contain olivine, clinopyroxene (diopside, augite), pyroxenoid (wollastonite), and garnet. Similarity in mineral assemblages could have resulted in misidentification of the unit as a kimberlite, rather than a skarn. The presence of pyroxenoids indicates a metamorphic origin (skarn) rather than igneous (kimberlite).

The location of the unit could also suggest a skarn rather than a kimberlite. The unit is located on the western-most ridge of White Mountain, which consists of marble. Marble is carbonate that has been metamorphosed by pressure and temperature. A hypothetical situation for the formation of this unit could be that an andesitic intrusion existed within the Bighorn Dolomite Formation (Ordovician), and Madison Limestone Formation (Mississippian) causing thermal metamorphism. The skarn would be located directly adjacent to the intrusion, where the temperature would be the greatest, causing a higher grade of metamorphism. The grade of metamorphism would decrease further from the intrusion, causing marble to form rather than skarn.

REFERENCES CITED

Anders, M.H., Craddock, J.P., Malone, D.H., Magloughlin, J.F., 2011, Heart Mountain and South Fork fault systems: Architecture and evolution of the collapse of an Eocene volcanic system, northwest Wyoming: Comment: Rocky Mountain Geology, v.46, no.1, p.71-75.

Beutner, E.C., Gerbi, G.P., 2005, Catastrophic emplacement of the Heart Mountain block slide, Wyoming and Montana, USA: GSA Bulletin, v.117, no. 5/6, p.724-735.

Beutner, E.C., Hauge, T.A., 2009, Heart Mountain and South Fork fault systems: Architecture and evolution of the collapse of an Eocene volcanic system, northwest Wyoming: Rocky Mountain Geology, v. 44, no. 2, p. 147-164.

Craddock, J.P., Malone, D.H., Magloughlin, J., Cook, A.L., Rieser, M.E., Doyle, J.R., 2009, Dynamics of the emplacement of the Heart Mountain allochthon at White Mountain: Constraints from calcite twinning strains, anisotropy of magnetic susceptibility and thermodynamic calculations: Geological Society of America Bulletin, v. 121, no. 5/6, p.919-938.

Geochemistry of the rocks oceans and continents, GEOROC database: http://georoc.mpch-mainz.gwdg.de/georoc/ (accessed February 2012).

Hague, T.A., 1982, The Heart Mountain detachment fault, northwest Wyoming: Involvement of Absaroka volcanic rock, *in* Geology of Yellowstone Park area:

Wyoming Geological Association, 33rd Annual Field Conference, Guidebook, p.175-179.

Hauge, T.A., 1990, The case for a continuous Heart Mountain allochthon, *in* Wyoming sedimentation and tectonics: Wyoming Geological Association, 41st Annual Field Conference, Guidebook, p.183-185.

Hauge, T.A., 1990, Kinematic model of a continuous Heart Mountain allochthon: Geological Society of America Bulletin, v. 102, p.1174-1188.

Malone, D.H., Craddock, J.P., 1995, Recent Contributions to the Understanding of the Heart Mountain Detachment, Wyoming: Northwest Geology, Manuscript.

Pierce, W.G., 1957, Heart Mountain and South Fork detachment thrusts of Wyoming: American Association of Petroleum Geologists Bulletin, v. 41, p. 591-626.

Pierce, W.G., 1975, Principal features of the Heart Mountain fault and the mechanism problem, *in* Geology and mineral resources of the Bighorn Basin: Wyoming Geological Association, 27th Annual Field Conference, Guidebook, p.139-148.

Pierce, W.G., 1982, Relation of volcanic rocks to the Heart Mountain fault, *in* Geology of Yellowstone Park area: Wyoming Geological Association, 33rd Annual Field Conference, Guidebook, p.181-183.

Pierce, W.G., 1987, The case for tectonic denudation by the Heart Mountain fault—A response: Geological Society of America Bulletin, v.99, p.552-568.

Willis, N.H., Pierce, W.G., 1983, Heart Mountain faulting: timing and mechanism, *in* Geology of the Bighorn Basin: Wyoming Geological Association, 34th Annual Field Conference, Guidebook, p.113-115.