“CHEMICAL FINGERPRINTING” OF VOLCANIC TEPHRA FOUND IN KANSAS USING TRACE ELEMENTS

by

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Abstract

Sedimentary beds rich in volcanic ash have been reported throughout Kansas. It is believed the source of these ashes are the large-scale eruptions from the Yellowstone Calderas. Very few of these ash units have been dated, however, and the vast majority simply reported as “Pearlette Ash.” The objective of this research was to investigate the potential of trace element geochemistry in correlating individual ash outcrops in Kansas to their eruptive source.

Thirty-six previously reported ash occurrences of unknown age in Kansas were reoccupied and sampled. In addition, three unreported ash deposits were discovered and sampled. Two ash units previously identified as Huckleberry Ridge-aged and three as Lava Creek B were also collected. The samples were processed using the method of Hanan and Totten (1998) to concentrate ash shards. These ash concentrates were analyzed for specific trace and rare earth element (REE) concentrations using inductively coupled mass-spectrometry (ICP-MS) at the University of Kansas.

The ash samples from known eruptions have distinct trace and REE signatures, allowing comparison to the unknown ash units. Most of the unknown ash samples correlate with specific Yellowstone eruptions. The majority of the undifferentiated “Pearlette Ash” samples correlate with the most recent Lava Creek B eruption and several unknown ashes correlate to the Huckleberry Ridge eruption. The distribution of ash units in Kansas being dominated by Lava Creek (0.60 ma) is expected because it is the most recent of the Yellowstone eruptions. The abundance of the older Huckleberry Ridge (2.10 ma) over the more recent Mesa Falls (1.27 ma) is likely the result of the much larger Huckleberry Ridge eruption.

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Dedication

I dedicate this research to my grandmother Ellen Whippi, who saw my potential and kept me on the correct road, even through my stubbornness. Thank you, for always standing in my corner, giving me words of encouragement, and never giving up on me!! I miss you more and more every day. I wish you could have lived long enough to see that all your hard-work in raising me finally paid off. Thank you and Grandpa Joe for always being there for me!!! I love the both of you.

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I further dedicate this research to the rest of my family. Thank you for your support, encouragement, and words of wisdom. I love you all very much! There are too many to name individually. Please don’t get offended if I didn’t mention you by name, but you know you’re in my heart.

Chapter 1 Introduction

Volcanic tephra has proven to be useful in establishing stratigraphic control for both site-specific and regional geologic studies and often provides absolute age constraints for sediments, structural features, depositional rates, biostratigraphic datum levels, and soil developments (Frye et al., 1948; Izett, 1981; Izett and Wilcox, 1982; Knott et al., 1999; Perkins et al., 1998; Perkins and Nash, 2002; Sarna-Wojcicki et al., 1979, 1984, and 1987; Sarna-Wojcicki and Davis, 1991; Sarna-Wojcicki, 2000; Swineford et al., 1955; Ward et al., 1993). For example, the Mid-West region volcanic tephra has proven to be a valuable tool used in the study of Pleistocene stratigraphy and has been used to develop both the rate of deposition and age of sedimentary deposits. Volcanic tephra has also been used to determine the timing and rate of movement along faults. Soil scientists have used tephra in the development of time lines for soil development. In addition, tephra discovered in the Gulf of Mexico region has also been used to control the biostratigraphic datum levels and have significantly contributed to identifying the age of these datum's as well as the timing and rates of deposition (Rather and Totten, 1999; Kachler et al., 2000; Totten et al.,2005).

The volcanic history of the western United States is extensive and voluminous. The volcanic history is directly linked to the various types of plate boundaries that have been associated with the western United States during the different periods of geologic time. As a result of these various types of plate boundaries the volcanic activity has ranged from localized eruptions of basalt to violent Plinian eruptions (Figure 1) that have spread tephra into wide-geographic areas (Sarna-Wojcicki and Davis, 1991; Izett, 1981; Luedke and Smith, 1991; Perkins et al., 1998; Wood and Kienle, 1990).

The Yellowstone Plateau volcanic field (YPVF) has produced multiple eruptions in the western United States over the last 16 Ma. These eruptions have left a series of large calderas across the Snake River Plain in the Yellowstone region, as the North American Plate migrated across the Yellowstone hotspot (Figure 2). The Yellowstone hotspot has produced three major volcanic eruptions over the last 2.2 Ma –Huckleberry Ridge (2.06 Ma), Mesa Falls (1.27 Ma), and Lava Creek B Tuffs (0.62 Ma) (Christiansen and Blank, 1972; Christiansen, 1982, 1984; Izett, 1981; Izett and Wilcox, 1982; Luedke and Smith, 1991; Hildreth et al., 1991; Perkins and Nash, 2002; Sarna-Wojcicki et al., 1984; Sarna-Wojcicki and Davis, 1991; Wilcox and Naeser, 1992).

In Kansas, abundant volcanic ash occurrences have been reported that are within strata of approximately equivalent age (Pleistocene) to the Yellowstone eruptions (Frye et al., 1948; Izett, 1981; Izett and Wilcox, 1982; Swineford et al., 1955). A small number of these ash occurrences have been correlated to their respective eruptive source (Figure 3). Some of the Kansas sites have been correlated with tephra's from the YPVF—i.e., the Huckleberry Ridge Tuff or Lava Creek B Tuff.

There still remains a substantial amount of tephra found in Kansas that remains undifferentiated (Figure 3). Collectively, these undifferentiated tephra have become known as the Pearlette Ash and was named by Cragin, F.W. in 1896 (Boellstorff, 1973; Cragin, 1896). Part of the reason for the lack of assignment to a specific eruption for many of the volcanic ash sites in Kansas is the lack of chemical analysis.

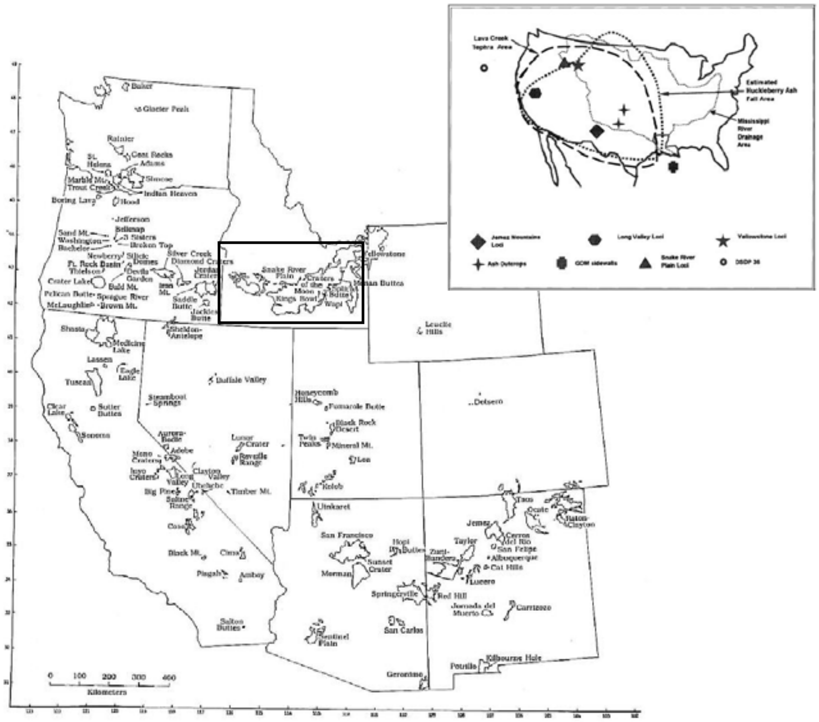

Figure 1. The volcanic history of the western conterminous United States for the last 16 Ma. This volcanic history has ranged from localized basalt eruptions to violent Plinian eruptions. Some of the most violent eruptions to occur over the last 2.2 Ma have come from the Yellowstone Plateau Volcanic Field (YPVF) outlined in red. The black box outlines the Snake River Plain. The inlet picture shows the distribution of tephra in the United States from the Huckleberry and Lava Creek B caldera's (modified from Hanan et al., 1998; Wood and Kienle, 1990).

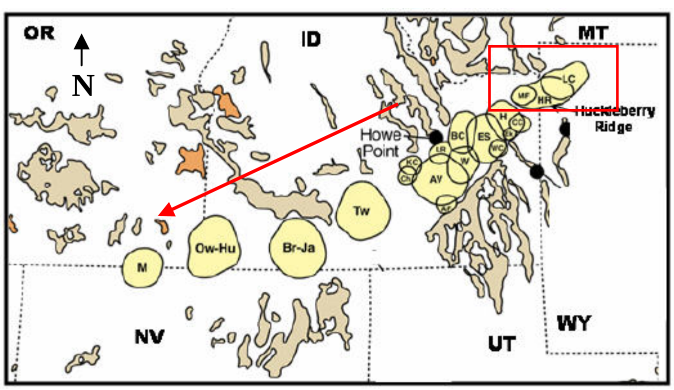

Figure 2. Advancement of the Yellowstone Plateau Volcanic field (YPVF) over the last 16 Ma. The oldest calderas point in the direction of the red arrow. The red box outlines the Huckleberry Ridge, Mesa Falls, and Lava Creek Caldera's. These 3 calderas are responsible for the most of the wide-spread ash fall to occur during the last 2.2 Ma in the conterminous United States (modified from Totten et al., 2005).

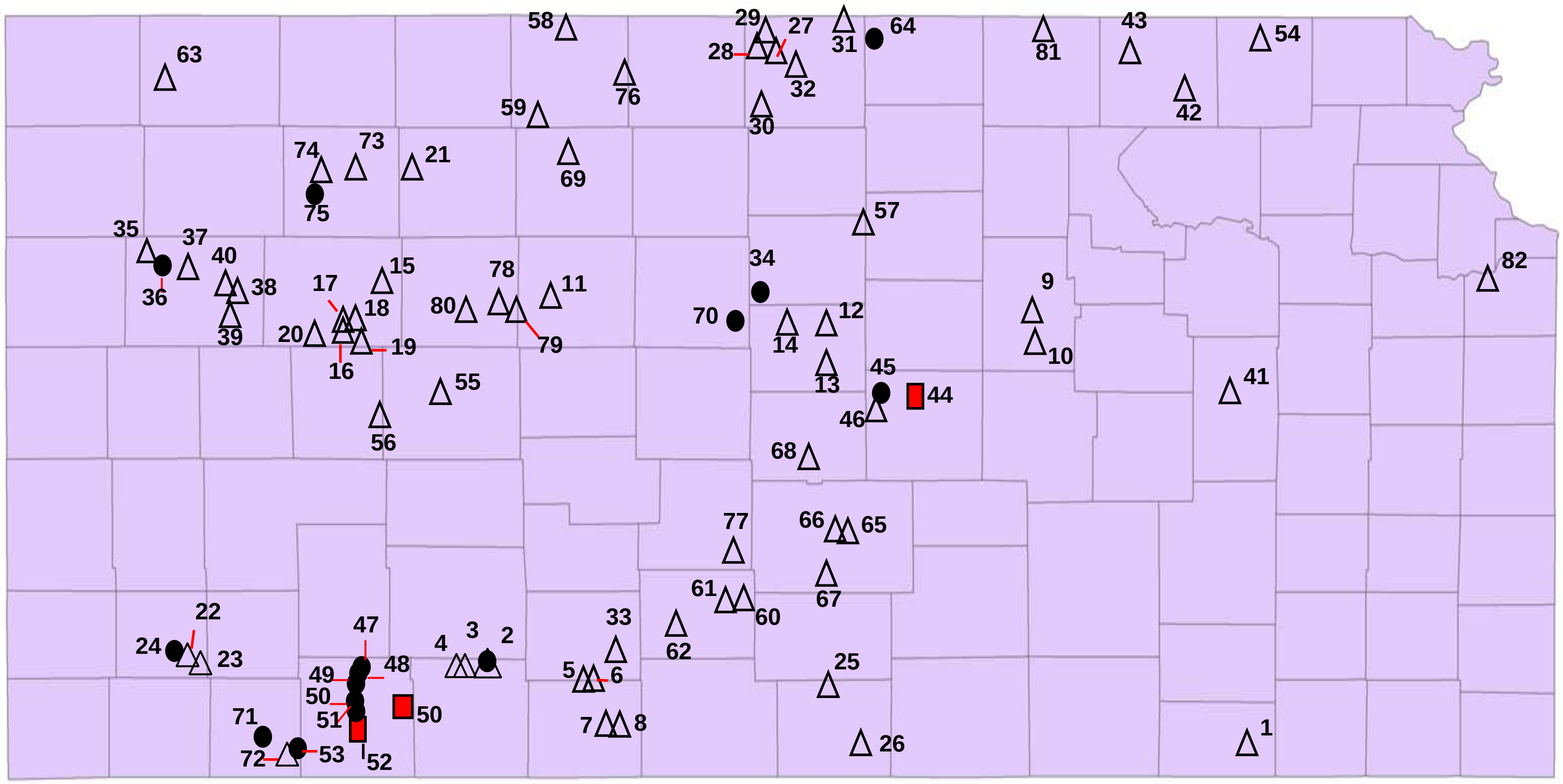

Figure 3. Documented outcrops of tephra found in Kansas according to Izett and Wilcox, 1982. Red boxes are documented outcrops of Huckleberry Ridge Tuff, Black Circles are documented outcrops of Lava Creek B Tuff, and open triangles are documented outcrops of Pearlette Ash. The Pearlette Ashes are undifferentiated tephra. Outcrop numbers are represented by KS-# within the report. Map was modified from Izett and Wilcox, 1982. See Appendix 2 for outcrop location and description of samples used in the current study. Map provided by www.esri.com.

The Cenozoic volcanic history of the western United States is extensive, so a great potential exists for the undifferentiated tephra found in Kansas to have an eruptive source other then the Yellowstone/Snake River region. The lack of chemical studies on this undifferentiated tephra ultimately deprives Kansas and the surrounding mid-continent region of a late Cenozoic timeframe. Establishing an effective timeframe for the ash found in Kansas could benefit various fields of research, such as: archeology, soil science, geology, paleoclimatology, stratigraphy, and paleontology. In addition, this research could reveal the originating eruption source (s) for the Pearlette Ashes in Kansas.

In addition to the abundant Pleistocene ash deposits, a number of Pliocene tephra's have been reported in Kansas. The age of these tephra units is based on paleontological data and known stratigraphic position (Swineford and Frye, 1946; Swineford et al., 1955). The Pliocene tephra are deposited within the Ogallala Formation (Swineford et al., 1955) and are identified as follows: Calvert, Rawlins, Fort Wallace, Dellvale, Reager, and Reamsville ash deposits (Figure 4). In the mid 1950's Swineford et al. conducted a petrographic and chemical study of this Pliocene tephra, and reported these tephra's to be rhyolitic in composition (Swineford et al., 1955).

In the past, researchers have attempted to differentiate the Pearlette ash found in Kansas with limited success. Previous researchers have focused on primarily analyzing the major elements of the Pearlette ash. Silica-rich volcanics from the entire Yellowstone/Snake River region have very similar major element composition, hence they are not easily discriminated from each other using these elements.

Objectives

The focus of this research will be on the Pearlette Ashes found in Kansas that have not been correlated to any eruption source. This research investigates whether the trace element compositions of these ash beds will be distinctive enough to recognize individual eruptions. Using inductively coupled plasma mass spectrometry (ICP-MS) the rare-earth elements (REE) and other trace-element concentrations were obtained and compared with known LCB, MFT, and HRT Tuffs from the Yellowstone Plateau Volcanic Field (YPVF).

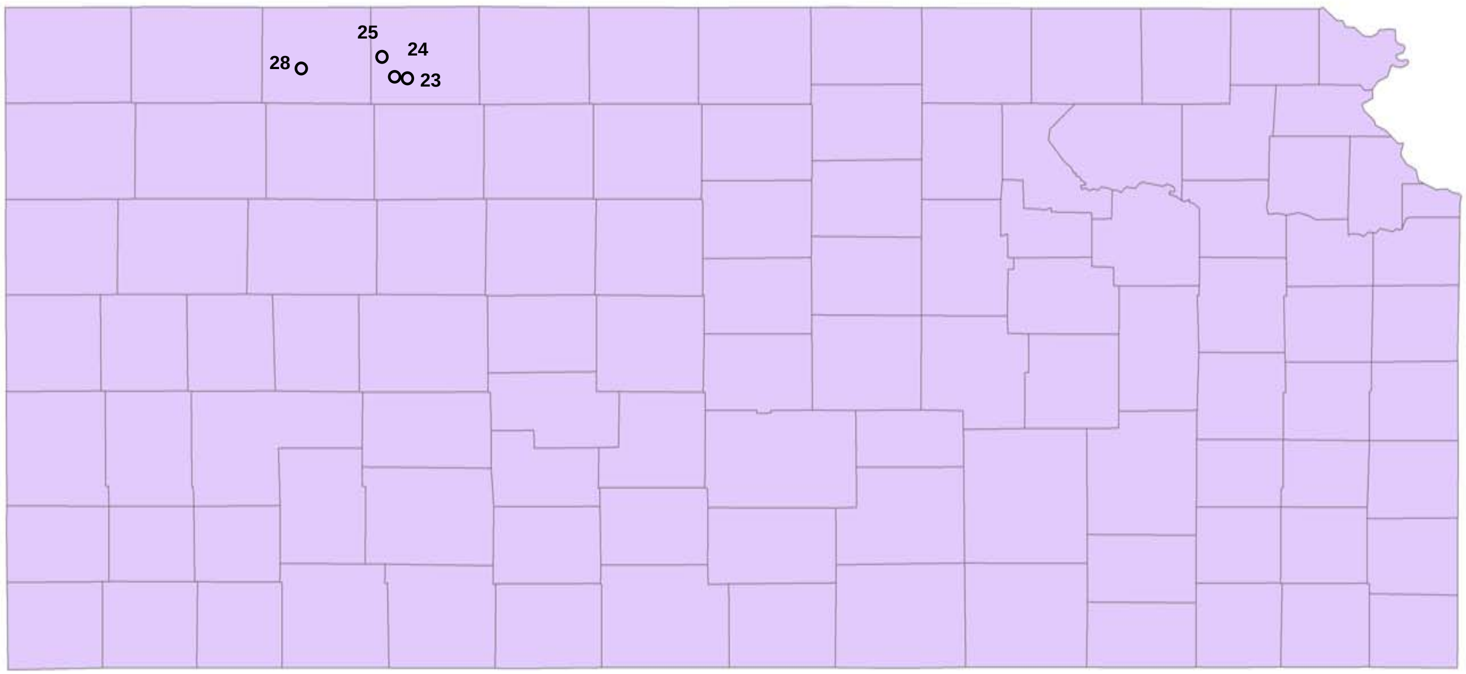

Figure 4. According to Swineford et al. (1955) these tephra outcrops are described as Pliocene based on stratigraphic position within in the Ogallala Formation. See Appendix 2 for outcrop description and exact location. Map provided by www.esri.com.

Chapter 2 Background

Late Cenozoic volcanism in the western United States has had an explosive and episodical history. The volcanism for this region (Figure 1) extends from east of the Rocky Mountains to west of the Cascades (Wood and Kienle, 1990). Early researchers who studied this volcanism lacked an explanation for the existence of volcanic activity for this region. It was not until the breakthrough of plate tectonics that the volcanic activity of the western United States was understood (Christiansen and Lipman, 1972; Lipman 1980; Lipman et al., 1971; Wood and Kienle, 1990).

Atwater (1970) suggested that a spreading center existed off the western coast of the United States until mid-Tertiary and that a subduction zone existed under the western United States. Later researchers showed that around 40 to 18 Ma the eastern limb of the East Pacific Rise (Farallon Plate) was subducting under the North American Plate and producing calc-alkaline volcanism (Atwater, 1970; Christiansen and Lipman, 1972: Lipman et at., 1971; Wood and Kienle, 1990). Around 30 Ma the East Pacific Rise collided with North America plate somewhere near the vicinity of northern Mexico (Wood and Kienle, 1990). This caused a changed in volcanism from calc-alkaline to a more mafic composition for the western conterminous United States (Christiansen and Lipman, 1972; Luedke and Smith, 1991; Wood and Kienle, 1990).

Evidence for this change is represented by large Miocene basaltic fields such as the Columbia River Plateau in Oregon, Washington, and Idaho, and the Snake River Plain in southeastern Oregon, lower Idaho, and northern Nevada (Luedke and Smith, 1991). The volcanism for the period of 10 to 16 Ma is not well represented in the rock record and appears to be randomly scattered (Christiansen and Lipman, 1972; Luedke and Smith, 1991). The volcanic rocks that date from 0 to 5 Ma do not appear to be quite as extensive or voluminous as the eruptions in the previous time periods. However, they do cover large areas of northeast California to southern Oregon, northern Nevada, southwestern Idaho, and the southwest and southern flanks of the Colorado Plateau with mafic rocks (Lipman, 1980; Luedke and Smith, 1991). During the late-Miocene period (10-5 Ma) the volcanic loci become fixed in the current positions we find them in today (Luedke and Smith, 1991; Wood and Kienle, 1990).

Volcanologists who studied the western United States were initially concerned with mapping and studying obvious stratovolcanoes—e.g., Mount St. Helens, WA, Mount Taylor, NM, and San Francisco Peaks, AZ. These early researchers did not fully understand the dangers posed to the people beginning to migrate into the western United States (Wood and Kienle, 1990). Many researchers were completely unaware of the large and dangerous calderas, such as, Yellowstone, Long Valley, and Valles Calderas. These volcanic loci have produced enormous eruptions during the late Tertiary and Quaternary periods (Luedke and Smith, 1991; Sarna-Wojcicki and Davis, 1991; Wood and Kienle, 1990).

Over the last 12 million years there have been numerous (Table 1) volcanic eruptions that have occurred in the western United States. Several of these volcanic eruptions have produced volcanic ash in excess of 100 km^3. The volcanic eruptions used in this study that have produced ash in excess of 100 km^3 are the Bishop Tuff, Lava Creek B Tuff (0.62 Ma), Mesa Falls Tuff (1.27 Ma), and Huckleberry Ridge Tuff (2.06 Ma). Respectively, each eruption produced 500 km^3, 1000 km^3, 280 km^3, and 2500 km^3 (Luedke and Smith, 1991; Sarna-Wojcicki, 2000; Sarna-Wojcicki and Davis, 1991).

Tuff Name	Location	Age	Reference
Lava Creek	Yellowstone Plateau, WY	0.61	Christiansen,1984
Bishop	Long Valley, CA	0.74	Bailey, et al., 1976
Upper Bandelier	Jemez Mts., NM	1.12	Self, et al., 1986
Mesa Falls	Yellowstone Plateau, WY	1.27	Christiansen,1984
Lower Bandelier	Jemez Mts., NM	1.45	Self, et al., 1986
Huckleberry	Yellowstone Plateau, WY	2.0	Christiansen,1984
Nomlaki	Cascade Range, CA	3.4	Sarna-Wojcicki,et al., 1991 (Denag)
Kilgore	Heise, Snake River, WA	4.3	Morgan, et al., 1984; Morgan, 1988
Walcott	Heise, Snake River, WA	6.0	Morgan, et al., 1984; Morgan, 1988
Black Tail Creek	Heise, Snake River, WA	6.5	Morgan et al., 1984; Morgan, 1988
City of Rocks	Picabo or Heise, Snake River Plain, ID	6.5	Leeman, 1982
McMullen Creek	Twin Falls, Snake River Plain, ID	8.6	Williams, et al., 1990
Wooden Shoe Butte	Twin Falls, Snake River Plain, ID	10.1	Williams, et al., 1990
Ann Arbor	Picabo, Snake River Plain, ID	10.3	Kellogg, et al., 1989
Sublett Range	Twin Falls, Snake River Plain, ID	10.4	Williams, et al., 1982
Wilson Creek	Twin Falls, Snake River Plain, ID	11.0	Ekren, et al., 1984
Grasmere	Bruneau-Jarbridge, ID	11.2	Bonnichsen, 1982
Cougar Point III	Bruneau-Jarbridge, ID	11.3	Bonnichsen, 1982
Browns Creek	Twin Falls, Snake River Plain, ID	11.4	Ekren, et al., 1984
Steer Basin	Twin Falls, Snake River Plain, ID	12.0	Williams, et al., 1990
Badlands	Humboldt, Snake River Plain, ID	12.0	Ekren, et al., 1984

Table 1. List major volcanic eruptions that have occurred in the western conterminous United States during the last 12 Ma (Modified from Hanan et al., 1998).

Three of the four eruptions came from the YPVF which consists of 3 different calderas, the Huckleberry Ridge, Mesa Falls, and Lava Creek Calderas (Figure 2). The driving mechanism for the YPVF is the Yellowstone hotspot (Perkins and Nash, 2002). The existence of the Yellowstone hotspot is not fully understood, however, the volcanism produced is well documented and remains of intense interest (Lipman, 1980; Perkins and Nash, 2002; Sarna-Wojcicki and Davis, 1991). Previous research by Perkins et al. (1998), Nash et al. (1997), Christiansen R.L. (1984), and Pierce K.L. and Morgan, L.A. (1992) has shown the YPVF is younger towards the northeast (Figure 2).

The YPVF is classified as a supervolcano field (Bindeman, 2006). The YPVF consists of three of the world's youngest supervolcano calderas: the Huckleberry Ridge, Mesa Falls, and Lava Creek Calderas (Bindeman, 2006). A supervolcano is a volcano capable of producing very large quantities of ash in a single eruption, usually in excess of 100 km^3 (Bindeman, 2006).

These supervolcanoes are exceedingly rare since they require enormous magma chambers. Two components needed to form these enormous magma chambers are a thick overlying continental crust and an intense heat source (Bindeman, 2006). World wide there are only 4 known regions that have expelled more then 700 cubic kilometers of magma during the past 2 Ma: Yellowstone National Park, WY, Long Valley, CA, Toba, Sumatra, and Taupo, New Zealand (Bindeman, 2006).

Typically these supervolcanoes are large bowl-shaped depressions that are several kilometers in length, width, and depth. These depressions usually form when the magma chamber empties out and the overlying rock is no longer supported and collapses downward. This is due to the pressure inside the magma chamber increasing with time. As time progresses more magma will collect inside the chamber and will be trap by the overlying rock. This increase in pressure will eventually raise the overlying rock creating vertical fractures. When a sufficient amount of vertical fractures form and reach the surface magma will eventually start to rise through these cracks forming individual volcanic vents. When enough of these vents merge a sufficient amount of magma is emptied and this causes the downward collapse of the overlying rock.

Kansas Volcanic Ash Deposits

Samuel Aughey was the first geologist in 1880 to describe tephra in Kansas and the surrounding central Great Plains. He initially described these deposits as scattered deposits of "white flour-like earth" and believed they originated from ancient geysers and hot springs and thus he named them geyserites (Aughey, 1880; Boellstorff, 1973; Wilcox and Naeser, 1992).

In 1885 Merrill first recognized the deposits described by Aughey contained fragments of pumiceous glass. He further described these deposits as volcanic dust and sand. Merrill believed that the glass was andesitic in composition (Boellstorff, 1973; Merrill, 1885).

Todd suggested in 1886 that the volcanic activity responsible for the tephra found in the mid-west region occurred at the same time as glaciation did in both the Dakota and Iowa regions. He further went on to propose that deposition of the tephra occurred in lacustrine environments. Todd, however did not suggest an eruption source for the tephra (Boellstorff, 1973; Todd, 1886).

It wasn't until 1894 that a proposed source area was suggested for the volcanic Tephra found in the mid-west region. Barbour was the first geologist to suggest that the source had to lie southwest of the mid-west region. His conclusions were based on the recognition of large calderas in New Mexico and Arizona (Barbour, 1894; Boellstorff, 1973).

Cragin in 1896 was the first geologist to formally name the tephra units found in Kansas. He named them the Pearlette ash after the Pearlette Post Office in Meade

County, Kansas. He assigned an age of late Pliocene based on three late Neocene terraces (Boellstorff, 1973; Cragin, 1896; Swineford and Frye, 1946; Wilcox and Naeser, 1992).

Haworth, in 1897 stated that the various tephra deposits, collectively named the Pearlette, show no evidence that would suggest a relationship exists between the different isolated deposits. The only probable conclusion that could be drawn is they may have formed around the same time. Haworth believed that using the words volcanic ash implied that the ash originated around the same time (Boellstorff, 1973; Haworth, 1897).

In 1916 Barbour conducted a detail description of the tephra found in the mid-west. He discussed the properties, origin, and uses of the tephra collectively known as the Pearlette. He also described other tephra he believed to be mid-Tertiary (Barbour, 1916; Boellstorff, 1973).

Landes in 1928 suggested the Capulin volcanic group from northeastern New Mexico was the originating source of eruption for the Pearlette ash. He based this conclusion on what he believed would have been prevalent wind directions at the time of eruption (Landes, 1928a, b).

Smith in 1940, studied the tephra in Kansas and Nebraska and then suggested the isolated bodies did not constituent a definite stratigraphic unit and thus should not be assigned a formal formation name. He looked at the tephra in Meade and Clark Counties, Kansas and deduced these deposits were most likely of a significant age difference. He noted that many of the tephra beds were tilted and some were more indurated than others. He suggested the tephra deposits were Tertiary in age (Boellstorff, 1973; Smith, 1940).

Swineford and Frye (1946) conducted an intensive study of the Pearlette ash that included chemical analysis and petrographic analysis (Swineford and Frye, 1946; Wilcox and Naeser, 1992). They concluded that volcanic ash found in Kansas and surrounding states occurred in several stratigraphic positions within Pliocene and Pleistocene deposits. This study revealed two different ash horizons, which possibly represent ash falls from the Pliocene Epoch. A second ash horizon was discovered and was believed to represent ash falls that occurred in the Pleistocene Epoch. According to this study Swineford and Frye concluded that the tephra naturally fall into two groups—one of mid-Pliocene and the other of mid-Pleistocene. This study looked at glass morphologies, index refraction, grain size (both of glass and minerals), and bulk chemical composition of the glass shards. It was determined that 14 out of the 16 tephra units studied could be grouped as Pearlette ash (Swineford and Frye, 1946).

In 1948 Frye et al. reported the Pearlette ash was rhyolitic in composition. They also argued that this ash was Early Yarmouthan in age. This was based on molluscan fauna found immediately below the ash (Boellstorff, 1973; Frye et al., 1948; Frye and Leonard, 1949).

In 1949 Ada Swineford formally suggested a source of eruption for the Pearlette ash. She concluded the Valles caldera was the source of eruption. She based this conclusion on Landes (1928) original hypothesis of wind direction and what she believed to be a similarity in glass morphology (Swineford, 1949; Boellstorff, 1973).

Swineford et al. (1955) suggested the possibility that some ashes found in the mid-west region could range in age from mid-Miocene to early-Pliocene. They show several locations in Kansas and Nebraska that contain late Miocene to early Pliocene tephra, based on stratigraphic position using the Ogallala Formation. In Kansas the counties of Rawlins, Wallace, Phillips, Decatur, and Norton tephra units are interbedded throughout the Ogallala.

Powers et al., in 1958 were the first researchers to recognize the possibility that the Pearlette ash was more widespread then previously thought. Research conducted suggests a similarity of Pearlette ash with previously unidentified tephra in Idaho, Nevada, and Utah. This notion is based on glass morphologies, bulk chemical analysis, and index of refraction (Powers et al., 1958; Boellstorff, 1973).

In 1961, Powers and Malde demonstrate that tephra beds separated by long distances could be used as stratigraphic markers. They showed tephra that was indistinguishable in the field could be distinguished from one another in the lab, based on chemical analysis of volcanic glass. Thus demonstrating a stratigraphic relationship existed between tephra beds separated by long distances (Powers and Malde, 1961; Wilcox and Naeser, 1992).

In 1960 Young and Powers studied the mineralogy of the Pearlette ash. From this study they suggested the Pearlette ash contains four separate ashes. This conclusion is based on the mineral Chevkinite (Young and Powers, 1960; Boellstorff, 1973).

In 1963 Swineford disputed the findings of Young's and Power's 1960 publication. She states that if the Pearlette ash were four separate ash falls there would be an observable difference in the volcanic glass. She states there are no apparent differences found in the glass. Swineford further goes on to suggest that for stratigraphic purposes the Pearlette can be considered a single deposit (Swineford, 1963; Boellstorff, 1973).

Wilcox suggested in 1965 the source of eruption for the Pearlette ashes located in Idaho, Utah, and Nevada is located in either California or Oregon. It is also suggested that there is a similarity between the volcanic tephra from the Yellowstone and the widespread Pearlette ash (Wilcox, 1965; Boellstorff, 1973).

Walker in 1967 conducted an intensive study of the Pearlette ash located in Nebraska and made the following conclusions:

1. Based on grain-size analysis there is no geographic trend, and thus no clear indication that grain-size can be used to differentiate the Pearlette.
2. Most of the deposits are very poorly sorted. The purer ash appears to be bimodal in grain-size and the silty ash seem to contain unimodal grain-size.
3. Mineralogically no distinction can be made between the Pearlette type ash and non-Pearlette ash.
4. The refractive index of the glass shards doesn't help to differentiate the Pearlette ash.
5. There is significant variability in the specific gravity of the glass shards.
6. The shard morphologies suggest at least two different eruption sources. But given the wide variability of the shape-class-percentages within a single ash unit, further studies need to be conducted. The shard morphologies alone are not enough to differentiate the Pearlette.
7. Using Major element analysis proved to be inconclusive. The similarity between the Pearlette ash is too great to yield differentiation. Thus suggesting the Pearlette was derived from a similar eruption source (Boellstorff, 1973; Walker, W.B., 1967).

Also in 1967 Izett proposed the first definitive clue the Pearlette ash most likely did not stem from a single eruption source, but, possibly from three different but similar eruptions (Wilcox and Naeser, 1992). This conclusion was based on his examination of mineral assemblages and volcanic glass properties of the Pearlette ash (Wilcox and Naeser, 1992). Around this same time the electron microprobe was introduced and quickly became a powerful quantitative tool for chemical analysis of major elements. This enabled Izett to further study and differentiate the Pearlette ash beds based on major elements (Wilcox and Naeser, 1992).

In 1970 Izett et al., published findings that showed there are four different Pleistocene ash beds: the Bishop, the Green Mountain Reservoir ash (Green Mountain, Colorado), and two Pearlette-like ashes. These two Pearlette ashes were collectively called Type-O from its occurrence at Onion Creek, Grand County, Utah and Type-S from its occurrence within the Sappa Formation, Harlan County, Nebraska. It is noted that at several locations there is a presence of two or more ashes at an individual location (Izett et al., 1970; Boellstorff, 1973).

In this same paper Izett et al. demonstrated the Pearlette ashes can be differentiated from other Pleistocene tephra based on increased Fe and Zn concentrations. In addition, they state the Pearlette ashes have a higher K_2O and Na_2O ratio then other Pleistocene ashes, e.g. the Bishop Tephra and Green River Mountain tephra. They further go on to state that the Pearlette ash is similar in composition to air-fall rhyolitic ash from the eruptive centers in Yellowstone National Park—i.e., Yellowstone hotspot and the Yellowstone National Park is most likely the eruption source for Pearlette ash. Albeit no evidence is provided for this conclusion except to say “preliminary work beyond the scope of this paper suggests the Yellowstone National Park is the source of eruption for the ashes collectively known as the Pearlette ash. That the proposed eruption source

(Jemez Mountain volcanic group in New Mexico) suggested by Ada Swineford in 1949 is wrong.” The authors state the Pearlette ash is both chemically and petrographically similar to the “gray-toned ashes common in the upper Miocene and Pliocene time periods” (Izett et al., 1970).

In 1971 Izett et al. found a third Pearlette-like ash they named Pearlette Type B, for the ash located at Borchers faunal locality, Nebraska (Boellstorff, 1973; Izett et al., 1971; Wilcox and Naeser, 1992). Further research indicated that two of the three Pearlette-like ashes chemically correlated with tephra originating from two of the three caldera-forming eruptions from the Yellowstone Plateau volcanic field. The Type-S correlates with tephra from the initial explosive phase of the middle ash-flow dated at 1.2 m.y. (K-Ar Sanidine)—Mesa Falls Tuff. The Type-O ash correlated with tephra from the initial explosive phase of the upper ash-flow dated at 0.62 m.y. (K-Ar Sanidine)—Lava Creek B (Wilcox and Naeser, 1992).

Borchardt et al., in 1972 demonstrated a distinction between Pleistocene tephra—e.g., Bishop Tuff, ash of Green Mountain Reservoir, and Pearlette-like ash based on trace-element composition. A similarity coefficient was introduced that evaluates the similarities between ash samples based on major-and minor-element concentrations. They analyzed 25 elements via neutron activation analysis and learned the most useful elements for distinguishing between the Pleistocene tephra are the Mn and Sm elements.

Izett (1981) studied a large number of ash deposits found within the United States. His major finding was that most ash could be divided into either rhyolite or dacite. The criteria used to divide the ashes into either rhyolite or dacite was the Ca, Mg, and K content of glass shards. The dacitic ashes tend to have higher Ca and Mg and smaller K concentrations in their glass.

Izett (1981) demonstrated that both trace elements and rare-earth elements (REE) could be useful in separating out ashes that have very similar major oxide analysis, or ashes suspected of being from the same source area. He further went on to suggest that the Europium anomaly, the fractionation of heavy REE and the fractionation of light REE would work best when determining ashes from similar eruption source(s).

In 1982 Izett and Wilcox composed a map of tephra distribution for the lower conterminous United States. The map showed all known major outcrops of volcanic ash for the conterminous United States. In Kansas, several localities were identified as Lava Creek B and Huckleberry Ridge Tuffs. However, large quantities of tephra were left undifferentiated in Kansas and marked on the map as Pearlette Ash.

Van Fleet (1999) studied the Pearlette Ash in Kansas to see if grain size analysis and X-Ray fluorescence (XRF) could be used to "fingerprint" the Pearlette Ashes to a known eruption source. Van Fleet was able to determine that grain size analysis could not be used to identify the source of eruption for an unidentified tephra. He concluded that grain size was more the result of the depositional environment then the source of eruption. Van Fleet concluded that using trace-elements was sufficient to "fingerprint" unidentified tephra's to an eruption source. This conclusion was based on separating known Huckleberry Ridge Tuffs and Lava Creek B Tuffs based on trace-element chemical composition.

Gulf of Mexico Ash

Previous work by Kratochvil (1997), Rather (1999), Kachler (1999), Jurik (2003), and Totten et al. (2008) have suggested that volcanic ash from the Yellowstone region is found offshore in the Gulf of Mexico in sediments that range in age from middle-Miocene to early-Pleistocene. The ash has been identified in well logs based on inverted SP and GR curves and decreasing density curves. The ash was obtained from well cuttings and side-wall cores and than compared with paleontological data in order to obtain age estimations of the sediment. The Pb-isotope signatures of the volcanic ash were compared with those of the Yellowstone region. Both methods were used by the aforementioned researchers and suggest the ash is indeed from the Yellowstone region.

A proposed method of transportation suggests that the Mississippian River Drainage System was overwhelmed with volcanic ash from the enormous eruptions (Kratochvil, 1997; Rather, 1999; and Jurik, 2003). Most likely ash from the Yellowstone /Snake River region was deposited into the Gulf of Mexico region within a short period of time (Jurik, 2003). The ash in the Gulf of Mexico appears to be deposited by turbidite deposits (Rather, 1999 and Kachler, 1999).

Totten et al. (2008) directly measured trace elements on volcanic ash found in the Gulf of Mexico. They looked at the rare-earth elements and other trace elements such as Ba, Sr, Rb, and Pb to see if such elements could be used to discriminate out individual eruptions. This research suggested that trace elements could be used to correlate unidentified eruptions to known eruptions with a certain level of confidence.

Trace Elements

Trace elements are defined as an element present within a rock in a concentration of less than 1 % wt (Rollinson, 1993) or less than a 1000 parts per million (ppm). Trace elements are used in geochemistry and petrology studies because these elements are more capable of discriminating between petrological processes then major elements (Rollinson, 1993). Trace elements are often classified into groups for geochemistry and petrology studies since the behavior of the elements are related to a particular group. The main groups of trace elements are divided into the following; 1) the first transition series, 2) the platinum group elements, and 3) the rare-earth elements (REE). A number of other elements are considered important when talking about trace elements and these elements are; Rb (atomic number 37), Sr (38), Y (39), Zr (40), Nb (41), Cs (55), Ba (56), Hf (72), Ta (73), P (15), Pb (82), Th (90), and U (92) (Rollinson, 1993).

The first transition series consists of the elements Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, and Zn (atomic numbers 21-30). The first transition series includes two major elements Fe and Mn. The platinum group elements are composed of Ru, Rh, Pd, Os, Ir, Pt, and Au (atomic numbers—44-46, and 76-79, respectively). The REE are comprised of Sc (atomic number 21), Y (39), La (57), and the lanthanides, which are the 14 elements that range from Ce (58) to Lu (71). However, in geochemistry and petrology studies the REE are often limited to Y (39), La (57) and the lanthanides (58-71) (Henderson, 1996). Thus this study follows the use of this limitation for the REE.

The purpose of grouping trace elements is to show the similar chemical behavior found between elements. This similar behavior is due to the fact that they also share similar chemical properties. When looking for some type of petrological process change it is often best to look for some type of deviation from the normal group behavior or for systematic changes of behavior.

The rare-earth elements (REE) are the most useful trace elements and demonstrate important applications in igneous, sedimentary, and metamorphic petrology (Rollinson, 1993; Henderson, 1996). The REE are usually sub-divided into the light REE and heavy REE. The light REE consist of atomic numbers 57-62 (La-Sm) and the heavy REE are atomic numbers 64-71 (Gd-Lu).

The REE have very similar chemical behavior and this results in similar physical properties. This similarity is attributed to the fact that all the REE are able to form stable 3+ ions that are of near equal size. However, there are a small number of REE that are able to exist in oxidation states other than 3+. The most important REE for geological processes are Ce^{4+} (relative oxidizing condition) and Eu^{2+} (relative reducing condition). The difference in size among these two elements and their 3+ counterparts is significant enough to cause changes in chemical behavior (Henderson, 1996).

However, despite having similar behavior the REE still have some small subtle differences that are directly attributed to the ionic size of each REE. These subtle differences are what causes REE to fractionate from one another. The REE have a smaller ionic radius with an increase in atomic number. However, special attention must be given to the fact that geological processes take advantage of the subtle chemical differences and can fractionate elements of one group from another.

Rare-earth elements (REE) should be normalized to a standard of reference and in most cases this standard of reference are chondritic meteorites when looking at igneous systems (Rollinson, 1993; Henderson, 1996). The reason for using chondritic meteorites is because they are thought to represent the unfractionated primitive solar system. There are two main reasons for normalizing REE. The first is because normalization removes the effects of the Oddo-Harkins Rule and the second reason allows for any fractionation of the REE relative to chondritic meteorites to be identified.

To date there is not a reference set standard used for normalizing REE and as a result several reference sets of standardized values have been introduced by various authors. Thus normalizing between various researchers is at best complicated. According to Henderson (1996) the most widely used Chondrite standards are of Wakita et al. (1971). This research uses the standards of Wakita el al. (1971) since the purpose of most graphs is for comparison with other graphs it was decided to use a referenced standard set in wide circulation.

Normalizing based on chondritic meteorites presents a number of problems. The notion that chondrite meteorites vary little in composition is delusive. When in fact there often is great variability in composition. This lends itself to some authors approaching the normalization process by averaging chondrite meteorites and others by assuming that the C1 chondrites are the most the representative composition of the original solar nebula (Rollinson, 1993).

The REE patterns seen in the REE plots or what are referred to sometimes as Masuda-Coryell diagrams, are the result of the chemical behavior of the REE and is controlled by the magma source and the crystal-melt equilibria that has occurred during the evolution of the magma chamber (Rollinson, 1993; Henderson, 1996). The chemical behavior of REE in magmatic systems does not allow the larger ion sizes of the REE to incorporate readily into common minerals. REE tend to have small mineral-melt partition coefficients (partition coefficient K, is the concentration of the element in the mineral divided by the concentration of the element in the coexisting melt) for minerals that have small cation coordination sites (Henderson, 1996). In a non-eccentric cooling magmatic system that contains minerals with small cation coordination sites the REE tend to be incompatible, that is the preferential place for REE to remain is the melt portion of a magmatic system (Henderson, 1996; Rollinson 1993). The overall partitioning of REE between a mineral and the melt doesn't only depend on the ionic radius but also depends on the ionic charge, temperature, pressure, and composition of the magmatic system (Henderson, 1996).

The REE Europium (Eu) exists in both a divalent (2+) and a trivalent (3+) oxidation state depending on the redox potential found in the magmatic system. The divalent state of Eu has a much larger ionic radius then the trivalent state, but despite a larger ionic radius the partition coefficient of the divalent state into some minerals is greater than that of the trivalent state. This especially can be seen when the cation exchange site has a divalent element and there is no additional charge requirements that need to occur at the site. A really great example of the partitioning behavior of Eu can be seen between the mineral plagioclase feldspar and a non-eccentric magma.

The relative partitioning difference found between the divalent and trivalent state of Eu can lead to a Eu anomaly. The Eu anomaly is defined as the deviation from the trend or patterns the other REE make on a normalized REE plot. The Eu anomaly can either be positive or negative depending on the direction of trend. A negative Eu anomaly will trend below the pattern of the other REE and a positive anomaly will trend above the REE pattern made on the diagram.

The Eu anomaly is the measured difference between the actual measured Eu value and a predicted Eu* anomaly value. The predicted Eu* value is calculated by averaging the Sm and Gd values—i.e., (Sm + Gd)/2 = Eu*. The actual Eu anomaly is determined by dividing the actual measured Eu by the predicted Eu*.

Sarna-Wojcicki et al. (1984), Ward et al. (1993), and Westgate et al. (1994) have demonstrated that using trace elements to correlate unidentified tephra's with tephra's from the Yellowstone Plateau Volcanic Field (YPVF) is possible. In addition, the works of Westgate et al. (1994), Pearce et al. (2004), and Knott et al. (2007) have demonstrated that using inductively coupled mass spectrometry (ICP-MS) is an effective method of measuring trace element concentrations in tephra used in the correlation of tephra.

Chapter 3 Methods

Investigation of 44 tephra samples from Kansas was conducted in two separate phases. The first phase consisted of fieldwork and the second phase consisted of laboratory work. The fieldwork was based on Izett and Wilcox's (1982) map that shows the distribution of various tephra found in the United States. Field collection was conducted within the state of Kansas and included collection of known Huckleberry Ridge Tuff, Lava Creek B Tuff, and a number of unknown tephra samples, collectively known as the Pearlette ash (See Appendix 2 for sample descriptions and pictures). Collection also included a number of Pliocene tuffs based on work from Carey et al. (1952), Swineford et al. (1955), and Frey et al. (1949).

Fieldwork

Izett and Wilcox's (1982) distribution map of tephra deposits give approximate locations of known outcrop samples in Kansas. The locations given in this map were based on a number of previous works in Kansas (Izett and Wilcox, 1982). When possible the original published work was consulted in order to get a more accurate description and location of tephra samples.

Locating samples was based on the Public Land System (PLS) used in the United States and the PLS for the United States includes a Township, Range, and Section. In many cases, more detailed spot locations were provided within the section. In addition, when it was possible topographical maps were used to aid in locating samples. The Kansas County Road Maps were consulted since they list all roads in a county and are based on the PLS used in Kansas.

A Global Positioning System (GPS) coordinate and waypoint was assigned to each tephra sample located in the field. All GPS coordinates are based on the North American Datum 83 (NAD83). The elevations are based on the North American Vertical Datum of 1988 (NAVD88). The NAD 83 datum is a revision of the NAD 27 and provides a more accurate horizontal measure then the NAD 27 (Wade, 1986). NAD 83 is a standard measurement of the earth's shape and size adapted by the International Union of Geodesy and Geophysics in 1979 (Wade, 1986). The North American Vertical Datum 88 (NAVD88) datum is based on the revision of the National Geodetic Vertical Datum of 1929 (NGVD29). NAVD88 provides a more accurate vertical measurement based on more vertical measurements and control points between Canada, Mexico, and United States (Wade, 1986).

Sample collection of the tephra was determined at each outcrop on an individual basis. The sampling of the outcrop was taken from the area that represented the purest and cleanest ash. Usually, this was in the base of an outcrop. Field identification of the tephra included examining a hand sample using a 10 X and 14 X magnification hand lens and determining if glass shards were visible in hand sample. Once this determination was made approximately ~15.00 cm of the surface was removed. Sampling of the tephra occurred from the newly exposed surface. When volcanic glass was not visible, or there was doubt about the purity of a sample a note was made and confirmed at a later time using a petrographic microscope. Approximately 5.00 kg ~10.00 kg of tephra was collected from each outcrop.

Each tephra sample was cataloged based on the county and assigned a unique GPS coordinate and waypoint using the following format: Waypoint #, Degrees, Minute, and seconds (39.00° 29.00’ 28.60”). The sample was double bagged and sealed using 2.5-gallon zip lock bags to minimize cross contamination of the samples. Each bag listed the county name, GPS, and datum. In addition, this information was stored in a field notebook. A picture was taken of each outcrop. The outcrop was assigned a field description that noted lithology above and below the tephra, general outcrop characteristics, and any unique features.

Laboratory Methods

Ash samples were prepared in the laboratory to help ensure a pure volcanic glass fraction without contamination. The samples were disaggregated using a mortar and pestal and sieved using a standard U.S. Sieve of 62.5 microns. The material finer than 62.5 microns was further sieved through a 20 microns microsieve using ultrasonic energy. The material coarser than 20 microns is free from clay-minerals. The ultrasonic energy also helps to clean the glass shard surfaces from any clay coatings (Hanan et al. 1998). The resulting material (<62.5 micron and >20 micron) is a combination of glass shards and silt-sized quartz and feldspar.

To further concentrate the volcanic glass, a heavy liquid separation was performed to sink the higher density quartz and feldspar from the glass shards using the method of Hanan and Totten (1998). Volcanic glass shards have a density of ~2.3g/cm^3 (Borchardt, 1970; Hanan and Totten, 1996; Hanan et. al, 1998; Totten et al., 2005; Van Fleet, 1999) compared to quartz and feldspar that have a density near 2.65g/cm^3.

The density separations were performed using Lithium Metatunsgate (LMT) adjusted to a density of 2.3 g/ cm^3. Previous work has established that a density of 2.3

g/cm^3 for LMT would separate pure volcanic glass from altered glass and heavy minerals—e.g., quartz, feldspar, and mica's (Van Fleet, 1999; Totten et al., 2005; Hanan et al. 1998; Kachler et al., 2000; Rather and Totten, 1999). The volcanic glass shards float and other minerals and altered glass sinks. The adjustment of the specific gravity of LMT is a rather straightforward process and can be manipulated either by evaporation or dilution with distilled water.

Approximately 20 grams of sample was mixed with 600 ml of distilled water to produce a slurry. This slurry was cleaned and disaggregated using a Fisher Scientific Ultrasonic Dismembrator Model 550. The slurry was treated for approximately 15 minutes.

Approximately 200 ml of the slurry mix was wet-sieved through a 62.5-micron (μm) sieve. This process was repeated until the entire mixture was sieved. The <62.5 micron fraction was wet-sieved through a 20-micron (μm) micromesh sieve and using ultrasonic energy from the 550 Ultrasonic Dismembrator. The fraction retained on the sieve was between 62.5 -20 microns. This size range was chosen because it yielded the most volcanic glass.

The slurry was dried in an oven at approximately 80° Celsius for 24 hours to ensure any distilled water added during the cleaning phase was removed. The samples were then mixed with approximately 30ml of 2.3 g/cm^3 Lithium Metatunsgate (LMT) in a 45 ml Nalgene™ centrifuge tube and allowed to set overnight. The tubes were then spun in a centrifuge at ~3100 rpm for 60 minutes. This enabled the "pristine" volcanic glass to float on top of the LMT and the heavy minerals/altered glass to sink.

The test tubes were placed in dry ice for approximately 30 minutes to freeze the bottom third of the LMT (with the associated minerals of >2.3g/cm3). The volcanic glass was then separated by unfreezing the upper portion of the LMT (containing the glass) with distilled water from a squirt bottle and washed onto a Millipore filter, and the LMT separated from the sample using a vacuum pump and suction flask. The glass fraction was rinsed several times with distilled water to ensure that all of the LMT was washed from the sample. The glass fraction was dried overnight in an oven at approximately 80° Celsius.

The glass fraction was viewed under a petrographic microscope to determine glass purity. The samples were then sent to the University of Kansas Plasma Analytical Laboratory (KU-PAL). The samples were analyzed for Rare-Earth Elements (REE) and other trace elements using a V6 Plasma Quad II+VS Inductively Coupled Plasma Mass Spectrometer (ICP-MS).

Chapter 4 Results

A total of 59 volcanic ash samples from Kansas were investigated in this study. There were 15 previously reported outcrops (Table 2) of volcanic ash that could not be located in the field. Five documented samples of volcanic ash from the Yellowstone region (Table 3) were collected, 2 ashes are reported as the Huckleberry Ridge Tuff equivalent and 3 are reported as the Lava Creek B Tuff equivalent (Izett and Wilcox, 1982). Included in this study were 29 undifferentiated Pearlette ash, 4 Pliocene ashes (Swineford et al., 1955), 3 unknown ashes from Van Fleet (1999) and 3 samples not previously described in the literature (Figure 5). These three samples were informally named BTD-KS-01, BTD-KS-02, and BTD-KS-03.

Tables 4 and 5 show the normalized values of rare-earth elements (REE) from ash beds located in Kansas that were used in this study (Appendix 1—lists raw concentrations and the Chondrite Standards used to normalize REE). Tables 6 and 7 lists other trace-element data obtained from these same ashes.

Table 2. Volcanic ash samples located in Kansas. During the course of this study these samples could not be located in the field. See Figure 3 and Appendix 2 for sample locations. Based on published work of Izett and Wilcox, 1982.

KS-12	KS-38	KS-45C
KS-13	KS-40	KS-54
KS-18	KS-42	KS-79
KS-35	KS-43	KS-81A
KS-36	KS-45B	KS-81B

Table 3. Documented outcrops of known Huckleberry Ridge and Lava Creek B Tuffs found in Kansas. Samples are based Izett and Wilcox's 1982 map. See Figure 3 and Appendix 2 for sample locations.

Sample			
Huckleberry Ridge Tuff (2.01 Ma)	KS-44	KS-52	
Lava Creek B Tuff (0.62 Ma)	KS-47	KS-49	KS-50

Table 4. Rare-Earth Elements (REE) concentrations normalized using Chondrite constant of Wakita et al., 1971. Concentrations are measured in ppm. See Table A1.3 in Appendix 1 for Chondrite Standards used to Normalize Rare-Earth Elements (REE).

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
KS-1	238.62	169.33	138.68	101.69	69.18	6.58	49.42	48.94	43.53	33.72	27.71	36.56	34.05	32.65
KS-4	228.09	164.52	133.47	98.05	68.87	5.62	50.04	50.64	45.67	35.38	29.28	39.69	36.59	34.41
KS-11	254.76	187.63	146.61	103.89	72.15	7.26	46.46	50.21	43.40	32.05	26.63	35.94	34.05	32.65
KS-15	238.41	175.23	137.44	97.66	68.97	6.44	46.12	48.30	43.13	32.18	26.09	36.56	34.32	32.94
KS-16	258.59	187.36	149.34	105.36	72.97	7.67	46.96	50.64	43.23	32.05	26.34	36.88	33.55	32.94
KS-16A	234.29	172.54	135.12	96.14	66.97	6.71	44.62	47.23	41.73	31.28	25.45	35.31	32.95	32.06
KS-17	256.97	185.98	147.52	104.34	72.87	7.26	47.69	51.06	43.83	32.82	27.31	37.50	34.41	33.24
KS-17A	240.47	176.46	138.60	98.23	69.38	6.30	45.77	49.79	42.97	32.18	26.59	36.88	34.14	32.65
KS-19	248.18	181.13	142.15	101.02	70.56	6.71	46.42	50.00	43.00	32.18	26.85	36.56	33.77	32.94
KS-20	258.68	187.04	148.60	104.31	71.38	7.67	45.62	48.30	41.57	30.38	25.30	35.00	32.00	31.47
KS-23	243.06	174.37	137.36	105.02	70.87	6.71	46.23	49.36	45.07	34.10	29.18	39.38	36.77	34.12
KS-26	245.94	178.85	142.15	103.97	70.62	6.03	50.00	50.64	44.87	35.00	28.78	38.44	35.64	34.71
KS-27	238.50	171.15	141.90	100.61	67.69	6.44	49.88	48.30	43.80	33.72	27.56	36.88	34.14	33.53
KS-31	251.35	176.73	145.45	106.09	71.64	7.53	49.96	50.64	44.43	34.87	28.85	38.44	35.59	34.12
KS-37	247.27	180.96	143.97	101.23	70.97	7.53	46.65	49.57	43.13	32.05	26.67	37.19	33.91	33.24
KS-39	228.85	169.02	134.21	95.06	70.10	5.75	46.54	52.13	45.43	33.85	28.24	39.06	36.32	35.00
KS-44	296.12	203.75	170.91	121.06	79.64	11.92	48.38	49.36	41.10	29.49	24.09	33.13	29.95	29.41
KS-46	247.53	180.99	142.23	101.09	69.13	7.12	45.77	47.87	42.00	31.28	25.59	35.94	32.59	31.76
KS-47	241.64	173.43	141.32	103.56	70.15	6.71	49.85	50.85	45.17	35.51	28.85	38.75	36.14	35.29
KS-49	255.76	176.58	148.93	108.03	72.36	7.12	50.81	50.00	44.17	34.62	27.92	37.81	34.91	34.12
KS-50	240.06	171.25	138.84	101.80	69.33	6.16	50.35	49.79	44.47	34.87	28.24	37.81	35.14	33.82
KS-52	293.76	211.23	168.10	119.78	79.64	11.78	50.54	51.70	44.00	32.31	26.49	36.25	32.82	32.94

Table 5. Rare-Earth Elements (REE) concentrations normalized using Chondrite Standards of Wakita et al., 1971. Concentrations are measured in ppm. See Table A1.3 in Appendix 1 for Chondrite Standards used to Normalize Rare-Earth Elements (REE).

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
KS-56	232.09	170.80	133.80	95.03	66.36	6.44	44.15	46.38	41.37	30.77	25.27	35.00	32.41	31.47
KS-58	91.79	68.36	57.11	45.20	27.85	13.70	16.12	13.83	11.33	7.56	6.06	9.06	7.41	7.35
KS-61	256.62	180.27	148.02	108.44	72.15	7.12	50.65	50.64	44.30	34.74	28.35	37.50	35.18	34.41
KS-63A	257.15	186.03	147.93	104.02	71.69	7.26	47.23	49.57	42.63	31.67	26.42	35.94	33.23	32.94
KS-63B	241.94	178.41	139.75	99.52	69.95	6.58	45.77	49.79	42.80	32.31	26.45	35.94	34.18	32.65
KS-67	212.79	155.08	120.66	93.22	61.69	8.22	40.12	41.91	37.53	28.72	24.37	33.44	31.05	28.82
KS-70	242.35	178.41	140.00	99.69	70.26	6.99	46.54	49.57	43.33	32.31	26.45	36.56	34.14	32.94
KS-74	258.85	189.07	147.36	104.55	72.15	7.26	46.23	50.00	42.63	31.54	26.02	35.31	33.45	31.47
KS-76	113.59	84.95	62.98	50.09	32.56	9.73	22.15	20.21	18.10	13.33	11.61	16.56	14.41	13.53
KS-78	266.18	194.42	152.15	107.91	73.90	7.67	47.19	50.85	43.33	31.92	26.31	35.31	33.55	32.06
ADA-23	194.41	139.02	111.16	76.39	45.64	11.92	29.96	28.09	24.83	19.10	15.81	21.88	20.82	21.18
ADA-24	223.79	158.46	127.85	89.64	53.59	10.14	36.85	33.83	29.77	23.08	18.75	25.63	23.59	24.12
ADA-25	116.79	88.95	70.41	55.25	33.85	12.74	20.15	18.09	15.47	10.90	9.07	13.13	11.36	11.18
ADA-28	244.35	175.75	134.79	101.30	59.95	11.37	37.04	37.02	33.30	25.00	21.76	30.00	27.95	26.47
RD-NL	92.41	45.96	61.40	45.70	28.82	13.01	13.69	11.06	8.10	5.00	3.73	5.00	4.41	3.82
RD-CL	262.85	188.52	146.12	100.97	63.64	11.64	38.27	38.51	33.07	24.62	20.43	28.44	26.23	26.76
RD-LA	81.91	43.36	50.17	36.80	22.41	13.70	11.77	10.43	8.13	5.38	4.19	5.63	5.00	4.41
BTDKS02	254.00	186.99	145.79	103.53	72.31	6.85	46.65	49.36	43.30	32.18	26.27	36.25	34.32	32.35
BTDKS03	249.59	184.37	144.05	102.27	72.15	6.85	47.12	50.00	43.93	32.69	26.77	37.19	34.82	33.24

Table 6. Trace element initial concentrations measured in ppm and obtained from inductively coupled plasma--mass spectrometry (ICP-MS).

Sample	Rb	Sr	Y	Zr	Nb	Cs	Ba	Hf	Ta	Pb	Th	U
KS-1	208.81	7.38	85.75	238.36	67.85	4.20	153.04	8.21	4.76	35.00	28.23	6.68
KS-4	223.78	6.37	89.90	230.04	70.75	4.53	131.17	8.26	5.10	34.76	29.80	7.35
KS-11	203.99	8.72	84.99	252.30	66.09	4.26	182.04	8.57	4.70	33.71	28.55	6.83
KS-15	206.76	7.41	84.77	228.94	47.56	3.76	148.88	7.95	1.43	30.23	27.38	6.91
KS-16	203.71	9.41	85.98	250.09	65.47	4.12	168.46	8.43	3.77	31.85	28.28	6.70
KS-16A	195.85	9.86	81.90	217.07	26.63	2.98	148.07	7.66	0.51	29.08	26.07	6.84
KS-17	214.23	9.13	88.04	250.98	69.09	4.42	162.35	8.56	4.06	32.72	29.14	7.04
KS-17A	213.74	10.34	86.18	238.77	68.68	4.52	150.11	8.33	4.06	32.93	28.87	7.09
KS-19	209.98	9.13	86.07	243.98	68.41	4.33	170.65	8.33	4.04	32.00	28.70	6.96
KS-20	189.53	8.98	80.89	246.11	62.65	3.82	176.02	8.31	3.67	31.14	28.28	6.38
KS-23	222.10	7.80	89.16	221.43	73.04	4.20	149.21	8.87	4.89	48.43	31.15	7.43
KS-26	215.23	6.14	88.87	241.36	70.10	4.28	153.37	8.45	4.98	40.72	29.93	6.98
KS-27	204.51	6.09	85.59	242.71	67.37	4.06	147.04	8.38	4.84	76.38	28.42	6.77
KS-31	217.03	13.23	88.66	243.63	70.05	4.36	213.77	8.48	4.94	51.59	30.02	6.99
KS-37	212.00	12.51	86.44	243.23	65.22	4.39	193.89	8.37	3.94	32.60	28.42	6.97
KS-39	229.86	10.38	91.38	231.52	70.50	4.99	133.13	8.13	4.93	34.34	29.69	7.76
KS-44	163.99	16.49	76.26	288.04	54.10	3.30	287.78	9.75	3.69	33.90	31.76	5.57
KS-46	192.00	7.48	82.15	221.66	26.57	2.66	166.95	7.79	0.47	26.56	25.89	6.64
KS-47	215.81	9.39	88.55	245.35	69.31	4.39	162.18	8.66	5.03	43.62	30.24	7.17
KS-49	205.00	11.06	86.42	256.58	69.13	4.20	183.26	8.94	5.10	45.77	31.47	6.66
KS-50	210.66	9.12	86.53	241.81	68.22	4.21	161.56	8.43	4.94	44.69	29.44	7.09
KS-52	195.58	14.40	85.42	290.65	58.31	3.70	394.64	9.39	3.41	34.95	28.78	6.66

Table 7. Trace Element Initial Concentrations measured in ppm and obtained from inductively coupled plasma—mass spectrometry (ICP-MS).

Sample	Rb	Sr	Y	Zr	Nb	Cs	Ba	Hf	Ta	Pb	Th	U
KS-56	191.91	8.78	81.48	209.19	25.90	2.51	155.63	7.33	0.50	25.94	24.88	6.69
KS-58	122.42	135.76	18.49	97.88	3.95	3.92	833.92	3.01	0.05	14.46	12.46	6.55
KS-61	208.48	6.57	86.64	257.31	68.40	4.00	185.39	8.82	4.84	46.27	29.53	6.75
KS-63A	204.97	7.92	85.73	251.33	66.20	4.23	183.26	8.49	3.83	31.35	28.16	6.75
KS-63B	207.68	7.28	85.57	242.09	64.91	4.32	150.93	8.19	4.80	32.65	27.67	6.76
KS-67	189.56	59.96	72.86	193.62	49.26	4.49	281.39	7.73	2.98	32.57	27.24	6.81
KS-70	209.72	9.51	86.00	239.58	64.92	4.46	164.21	8.20	4.81	33.08	28.35	6.82
KS-74	200.39	9.06	84.03	250.77	64.48	4.08	179.35	8.36	4.55	32.01	27.34	6.70
KS-76	117.41	208.81	33.85	120.10	2.29	4.15	443.09	3.98	0.03	21.76	13.91	4.55
KS-78	201.57	8.12	85.06	258.95	64.87	4.12	189.85	8.54	4.66	32.06	27.90	6.49
ADA-23	177.83	49.60	48.52	358.62	39.20	3.81	923.31	9.82	3.11	26.26	29.46	7.49
ADA-24	175.69	21.39	58.57	346.79	1.83	1.85	505.97	9.41	0.05	20.28	30.12	7.82
ADA-25	113.61	135.81	27.38	189.66	3.79	1.77	1181.14	5.46	0.03	13.81	18.00	9.30
ADA-28	189.49	33.73	63.80	247.57	10.81	3.03	610.89	8.54	0.12	22.64	34.48	9.01
RD-NL	42.36	156.02	12.41	54.22	1.89	0.35	535.89	1.41	0.19	3.15	4.98	16.52
RD-CL	206.12	26.29	64.85	414.70	42.27	4.23	666.69	11.18	2.71	29.29	34.44	2.71
RD-LA	75.63	269.50	14.22	51.06	1.57	0.36	911.50	1.43	0.25	6.54	5.21	4.96
BTDKS02	204.53	8.79	85.85	251.15	65.69	4.22	170.09	8.50	4.78	32.60	28.02	6.63
BTDKS03	207.60	9.31	86.69	247.81	65.80	4.35	167.78	8.44	4.81	33.07	28.55	7.07

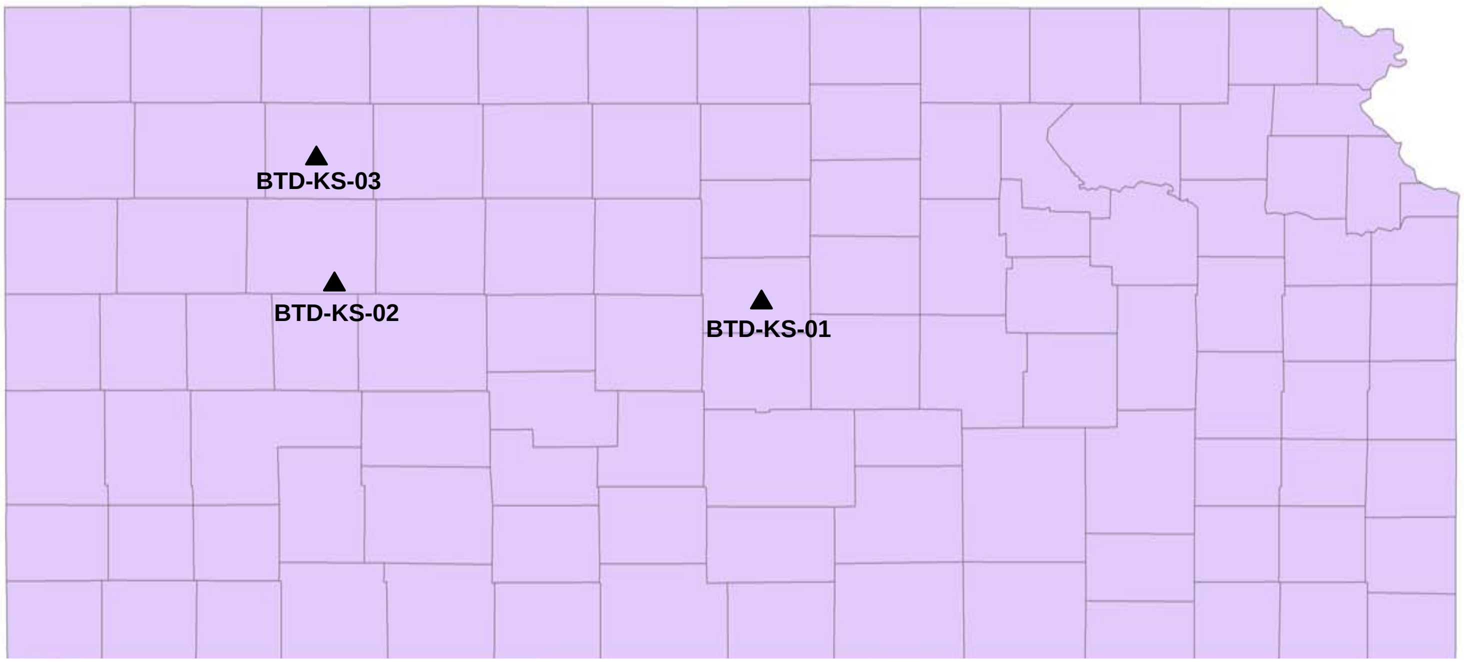

Figure 5. These tephra outcrops are not previously described in the published literature. BTD-KS-01 is found in Ellsworth County, Kansas, BTD-KS-02 is found in Gove County, and BTD-KS-03 is located in Sheridan County, Kansas. See Appendix 2 for exact location and field descriptions. Map provided by www.esri.com.

Chapter 5 Discussion

In this study Rare-Earth Element diagrams, other trace-element ratios, and spider diagrams were constructed to determine if trace elements could be used to fingerprint undifferentiated ashes, and subsequently correlate them to ashes from the Yellowstone region using published data. Data from Totten et al. (2008) were used because this study obtained trace element concentrations through inductive coupled plasma mass spectrometry (ICP-MS) on glass shards, which is the same method used to obtain the chemical data in this study.

Characterization of Samples from Known Sources

Initially, this study compared several dated Huckleberry Ridge and Lava Creek B Tuffs found in Kansas and a Mesa Falls Tuff (GOM 11) of Totten et al. (2008) using trace element chemistry. According to Izett and Wilcox, 1982 the Kansas localities of KS-44 and KS-52 have been correlated with the Huckleberry Ridge eruption and the Kansas localities of KS-46, -49, and -50 have been correlated to the Lava Creek B eruption. Using Rare-Earth Element (REE) chemistry, trace element ratios, and spider diagrams it becomes apparent that these “suspected/known” Yellowstone samples that were collected in Kansas correlate very well with the each other (Figures 6-11).

In Figure 6, the pink squares represent the Lava Creek B eruption (0.62 ma), the orange squares are the Mesa Falls eruption (1.27 ma), and the blue diamonds are the Huckleberry Ridge eruption (2.01 ma). Despite the age difference among these ashes they all have a similar REE chemistry. There are slight variations which allow the tuffs to be differentiated. There are slight variations in the fractionation of the light rare earth elements (La-Sm) between the eruptions. Each eruption appears to have a distinct negative Eu anomaly, controlled mainly by early crystallization of feldspar. A felsic magma chamber like Yellowstone would have more time to crystallize feldspar via crystal fractionation and the subsequent melt would become more and more depleted in the divalent Eu.

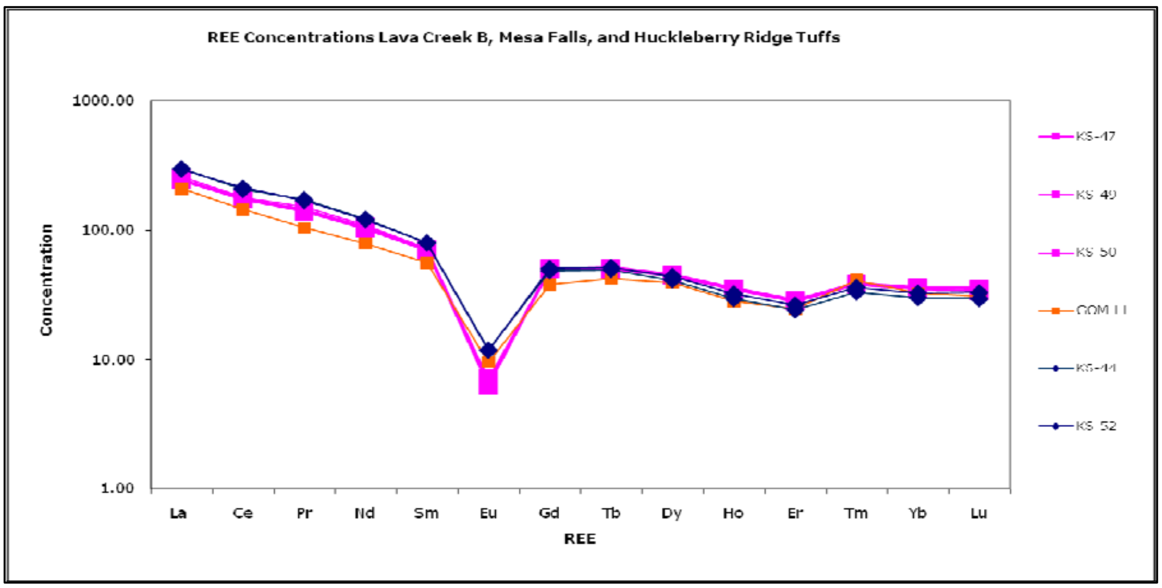

Figure 6. REE plot showing the overall trend of the REE patterns seen in the Lava Creek B (Pink Squares), Mesa Falls (Orange Squares), and the Huckleberry Ridge (Blue Diamonds) Tuffs. GOM 11 was taken from Totten et al., 2008, and is a published Mesa Falls Tuff. KS-47, -49 and -50 are dated Lava Creek B Tuffs located in Kansas and KS-44 and KS-52 are dated Huckleberry Ridge Tuffs also located in Kansas (Izett and Wilcox, 1982). The dated LCB, MFT, and HRT found in Kansas share a very similar REE pattern. The Eu anomaly helps distinguish the individual eruptions.

In Figure 7 the Ba/Rb Vs Sr/Rb ratios are plotted for the Lava Creek B, the Mesa Falls, and the Huckleberry Ridge eruptions (using the same color scheme in Figure 6). These ratios clearly separate each of the ashes into their distinct eruptions. The Mesa Falls eruption has the highest ratio values, the Huckleberry Ridge appear to plot in the middle, and Lava Creek B eruptions have the lowest ratio values. In general, each of the different eruptions tends to cluster. One problem is the lack of samples for Mesa Falls Tuff so a defined field cannot be established.

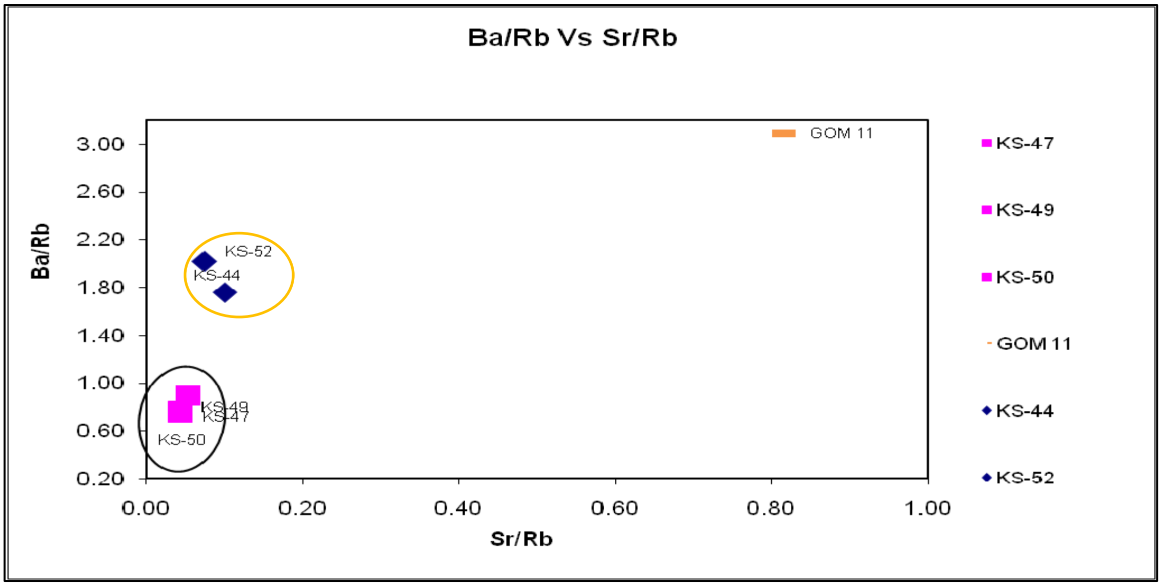

Figure 7. Ba/Rb Vs Sr/Rb ratios for the tuffs from the Yellowstone Region—i.e., the Huckleberry Ridge (Blue Diamonds), Mesa Falls (Orange Bar), and the Lava Creek B (Pink Squares) Tuffs. The samples represented are previously published samples from Totten et al. 2008 (GOM 11, Mesa Falls Tuff), and dated Yellowstone samples located in Kansas (KS-47, -49, and -50, Lava Creek B Tuffs and KS-44 and KS-52 which are Huckleberry Ridge Tuffs (Izett and Wilcox, 1982). Ba/Rb Vs Sr/Rb ratios distinctly identifies each of the last three major eruptions to occur from the Yellowstone Plateau Volcanic Field—i.e., Huckleberry Ridge, Mesa Falls, and Lava Creek B Tuffs.

Figure 8 plots the Zr/Rb Vs Sr/Rb ratio's for the Yellowstone Tuffs using the same color scheme as prior figures. These values for each of the individual eruptions appear distinct enough to separate these eruptions. Again the lack of samples for the Mesas Falls Tuff is a hindrance, but it appears that the Mesa Falls Tuff plots in a different region of the bivariate plot, suggesting it is a good indicator of the subtle differences seen within the trace element chemistry. The Huckleberry Ridge Tuffs have higher Zr/Rb value than both the lava Creek B and Mesa Falls Tuff. The Sr/Rb values for the Lava Creek B appear to be constant, while the Huckleberry Ridge Tuffs has a slight variation.

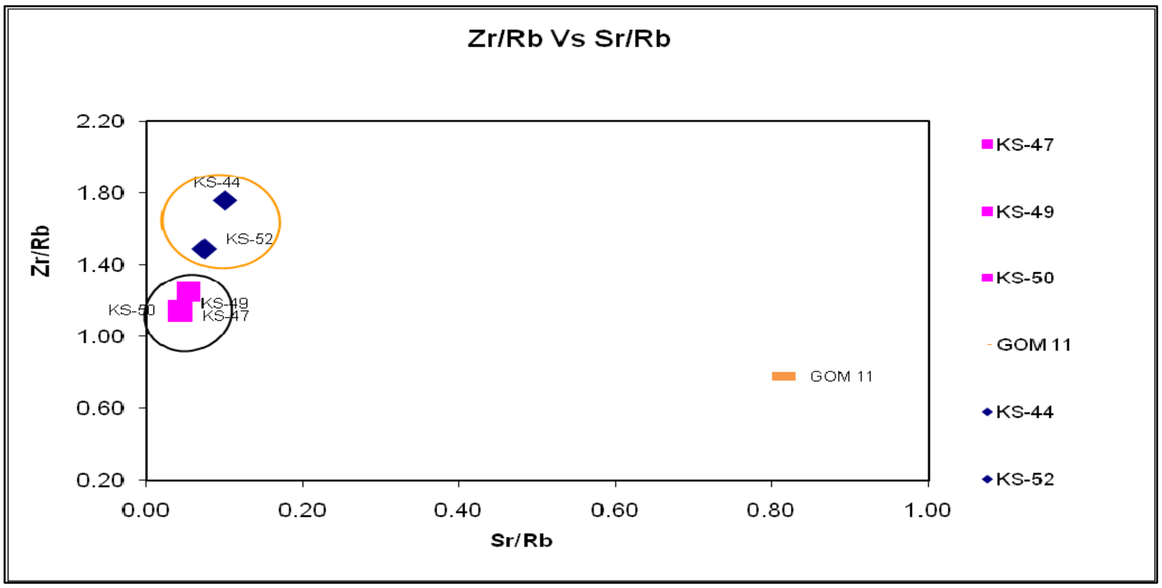

Figure 8. Zr/Rb Vs Sr/Rb ratios are for the Huckleberry Ridge, Mesa Falls, and Lava Creek B Tuffs of the Yellowstone region. These samples are from Totten et al. 2008 (GOM 11) and the dated Kansas samples (KS-??) based on Izett and Wilcox's map of 1982. The Zr/Rb Vs Sr/Rb ratios clearly distinguish the individual eruptions from one another.

La/Lu Vs Europium anomaly is plotted on a bivariate plot in Figure 9 (same color scheme as previous figures). La/Lu ratio shows the fractionation over the entire REE—i.e., it is a measure of the LREEs to HREEs, and this is plotted against the Eu anomaly. The ratios allow a distinction to be made between individual eruptions. Huckleberry Ridge Tuffs have higher La/Lu values than the Lava Creek B or Mesa Falls Tuff. The Mesa Falls Tuff has higher Eu anomaly values then Huckleberry or Lava Creek B Tuffs. A slight spread is seen in the Eu anomaly amongst the Huckleberry Ridge and Lava Creek B Tuffs.

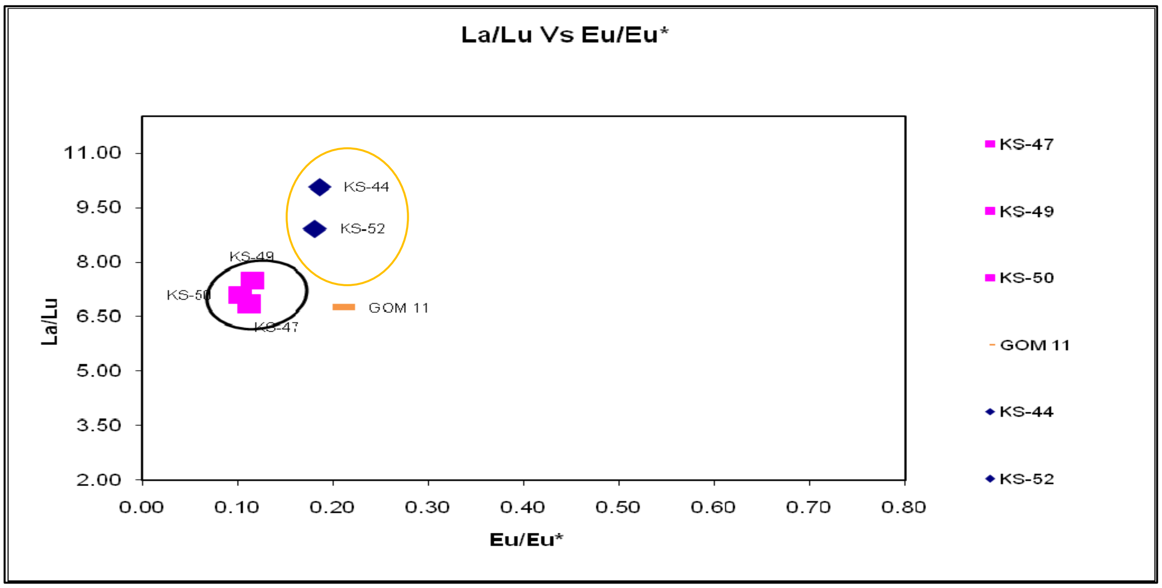

Figure 9. La/Lu Vs Eu/EU* ratios for the Huckleberry Ridge, Mesa Falls, and Lava Creek B Tuffs of the Yellowstone Plateau Volcanic Field are shown above and represent both previously Totten et al. 2008 (GOM 11) and the dated Yellowstone samples found in Kansas (Izett and Wilcox, 1982). These ratios represent the total fractionation of Rare-Earth Elements and clearly help to separate out the individual eruptions of the Yellowstone Plateau Volcanic Field.

Figure 10 shows the La/Sm Vs Eu anomaly which demonstrates the variation between the Eu anomaly and the fraction of the LREEs. These ratios discriminate individual eruptions from the Yellowstone region. These values do not differentiate the individual eruptions as clearly as Figure 9.

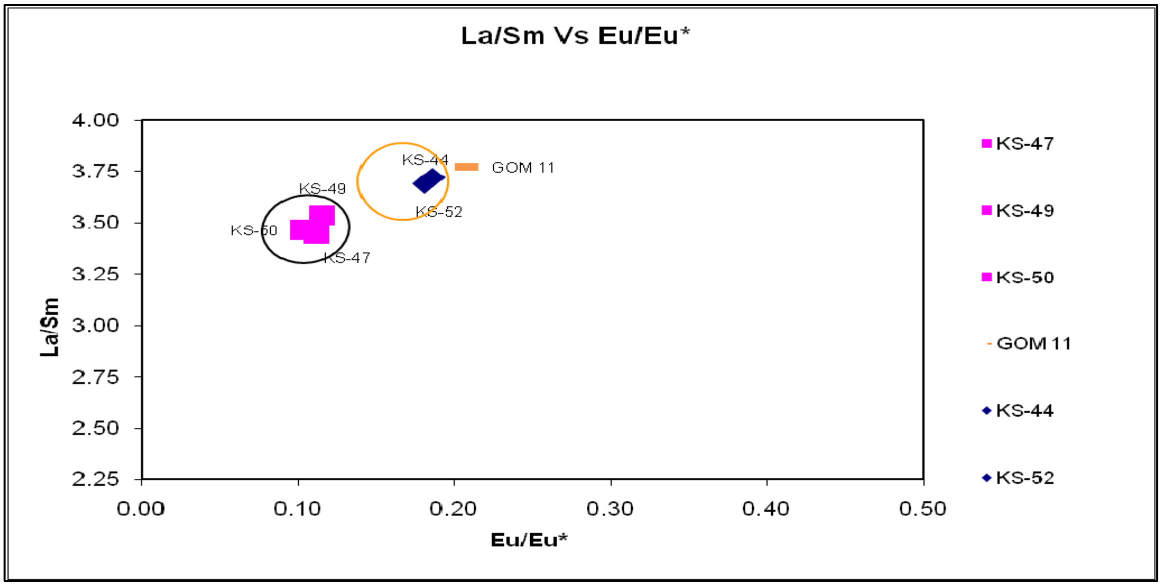

Figure 10. La/Sm Vs Eu/Eu* ratios are for the Huckleberry Ridge, Mesa Falls, and Lava Creek B Tuffs of the Yellowstone region. These samples represent the published samples Totten et al. 2008 (GOM 11) and the dated Kansas samples. These ratios show the fractionation of the Light Rare-Earth Elements and clearly distinguish the individual eruptions from one another.

Figure 11 is a spider diagram for all of the published ashes from the Yellowstone region as seen in the previous figures. The diagram shows the greatest variability among the more mobile elements like Sr, Rb, and Ba. Each individual eruption tends to show a similar degree of variability among themselves. In the elements that are considered to be immobile (less mobile) there is less variation.

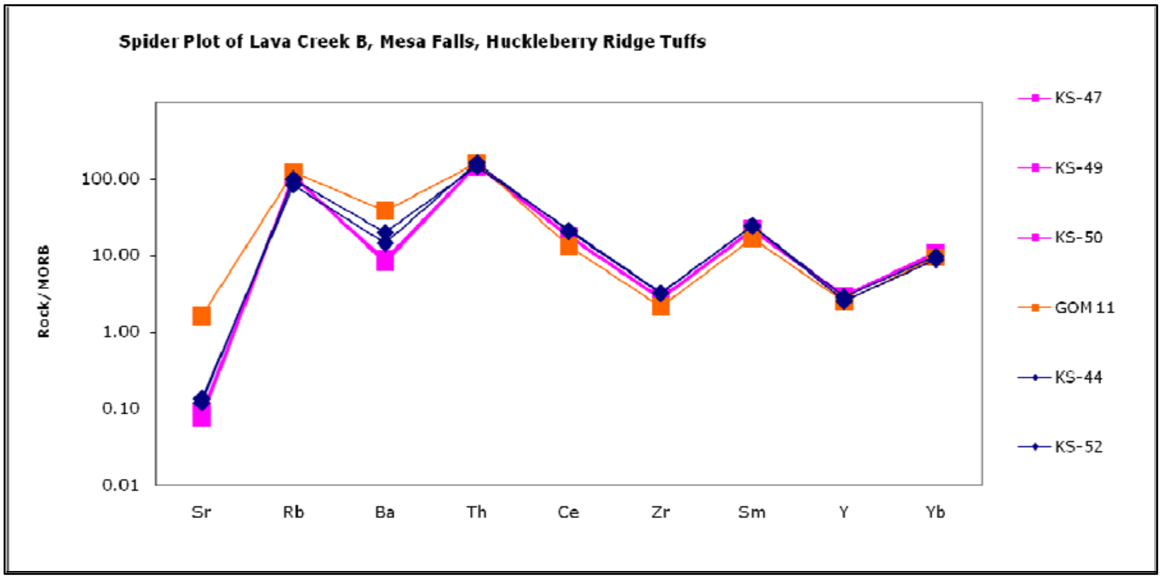

Figure 11. Spider of the Huckleberry Ridge, Mesa Falls, and Lava Creek B Tuffs. The more mobile elements like Sr, Rb, and Ba show the greatest variability and could be the result of magmatic differentiation. In the least mobile elements like Th, Ce, Zr, Sm, Y, and Yb there is little variation seen among the different tuffs. The plot helps support the notion that these tuffs share similar trace element chemistry. Elements normalized to the MORB standards of Pearce, 1983.

Trace element variation between Yellowstone Tuffs of known eruptive source, collected in Kansas allows each ash to be distinctly recognized. The following section will compare ashes of unknown source to these data.

Correlation of Undifferentiated Samples

The initial steps of this study suggest that trace elements are useful to "fingerprint" tephra's from specific eruptions. The next logical step is to compare the undifferentiated tephra samples found in Kansas with the known samples from the Yellowstone region.

During the course of this study the unknown ash samples collected in Kansas were divided into 4 sets and are listed as follows; 1) Pearlette Ash samples, 2) BTD-KS (unpublished new discoveries), 3) Pliocene ash, and 4) those unpublished ash samples from Van Fleet, 1999. This division was based on who previously reported the sample locations—e.g., Swineford et al. 1955 published the samples labeled Pliocene Ash; Pearlette Ash samples were reported by Izett and Wilcox, 1982; Van Fleet, 1999 reported 3 new ash localities, and the BTD-KS samples were discovered during this research. Figures 12 and 13 are the REE plots and spider diagrams for all of the unknown ash samples collected in Kansas. Each set is discussed in the following paragraphs.

Figure 12 shows each of the four unknown sets using REEs to show the variation among each group. All of the plots show a similar pattern, excluding the outliers that do not correlate with any Yellowstone Tuff—e.g., KS-58, -76, RD-NL, RD-LA, and ADA-25. The Eu anomalies appear to correspond with the appropriate Yellowstone eruption.

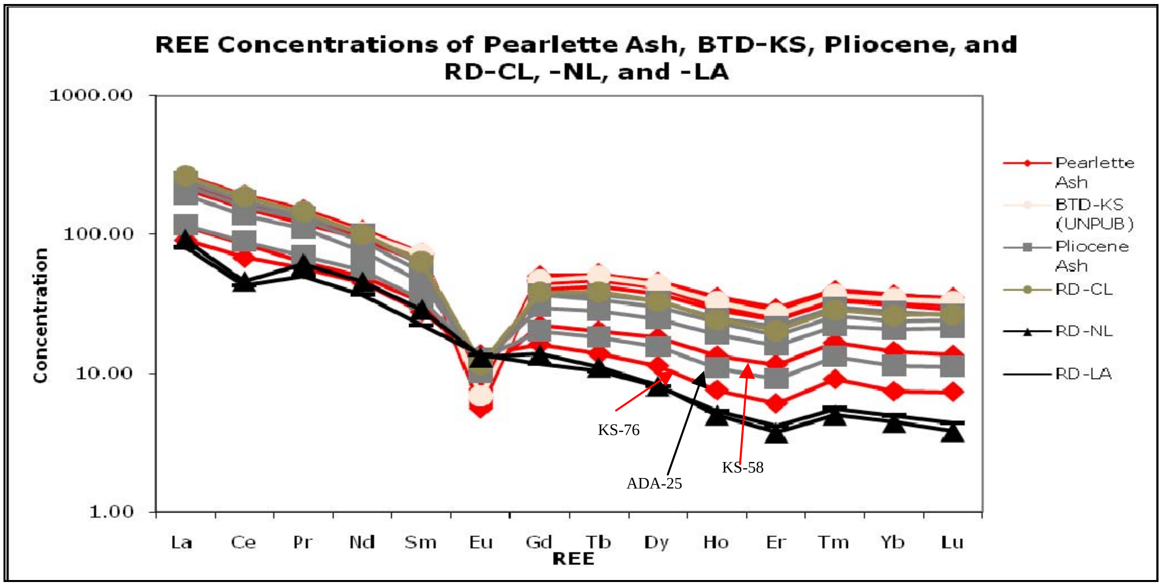

Figure 12. Rare-Element plots of the unknown tephra's collected in Kansas for this study. The red triangles represent undifferentiated Pearlette Ashes found in Kansas (Izett and Wilcox, 1982), the light-tan circles represent ash samples discovered during the course of this study, BTD-KS, these samples have not been published in prior literature, the dark-gray squares are Pliocene Ashes (Swineford et al.1955), and the RD-CL, RD-NL, and RD-LA are unpublished samples that Van Fleet, 1999 collected in Calvert, Norton, and Almena Counties, respectively.

The overall trend using spider diagrams for each of the 4 sets of undifferentiated ashes found in Kansas is shown in Figure 13. Among the individual sets the variation is very similar, with the exception of the same outliers (KS-58, -76, ADA-25, and RD-NL and RD-LA) previously identified. The most variation is seen among the elements that have been shown to be mobile. In the less mobile elements—e.g., Th, Ce, Zr, Sm, Y, Yb the variation in each set is minimal. This supports the notion that these tuffs have been derived from a similar magma source.

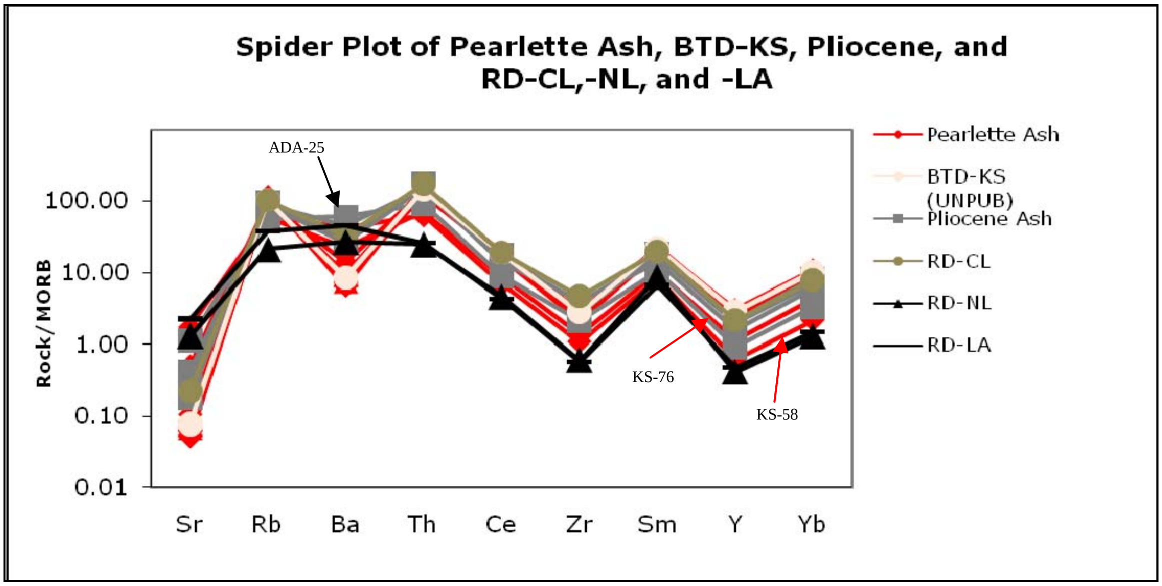

Figure 13. Spider plot is of the Pearlette Ashes, unpublished BTD-KS samples, the Pliocene samples, and the RD-CL, -NL, and -LA samples collected in Kansas and used in the current study. Elements are normalized to the MORB standards of Pearce, 1983.

Pearlette/Previously Unreported Ashes of Kansas

In total, 27 undifferentiated Pearlette Ashes from Izett and Wilcox, 1982 were analyzed using REE (Figure 14-15), trace-elements ratios (Figures 16-19), and Spider Diagrams (Figures 20-21). Twenty-five out of the 27 Pearlette Ashes studied could be correlated with the Lava Creek B Tuff. The remaining 2 Pearlette Ashes (KS-58 and KS-76) could not be matched confidently to any tuff from the Yellowstone Region (Figures

15-19 and 21). In addition, two Pearlette Ash samples KS-45A and KS-45B did not yield volcanic glass in the laboratory to conduct a chemical analysis.

In Figure 14 some of the Pearlette Ash samples have been plotted against the known Lava Creek B Tuffs used in this study. The REE plots show similar distribution between the averaged knowns and the undifferentiated Pearlette Ashes. These samples are sourced by the Lava Creek B eruption.

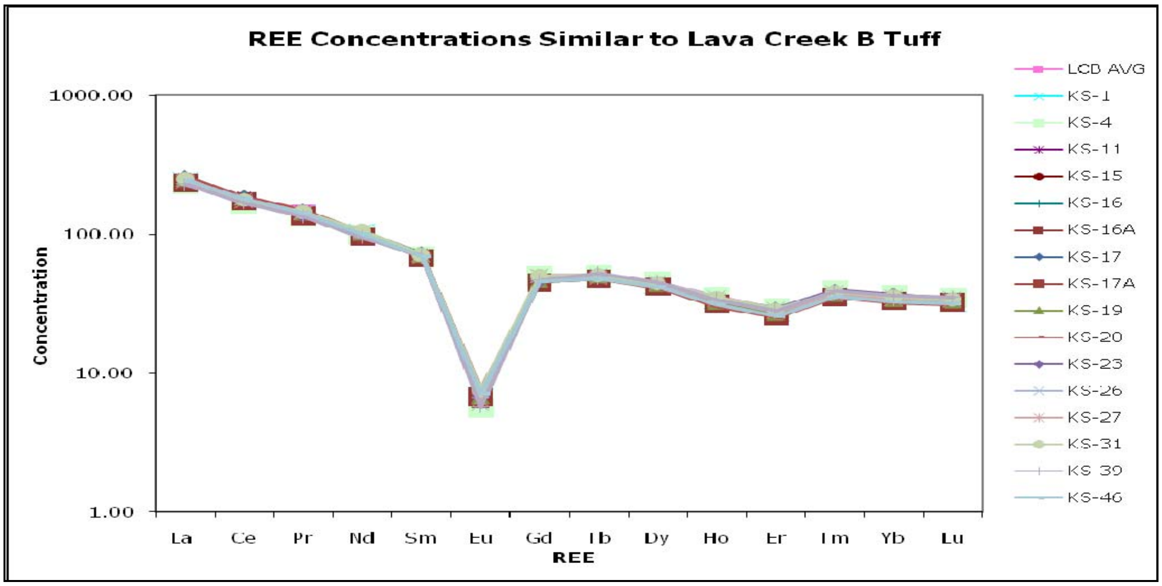

Figure 14. Previously dated outcrops of Lava Creek B Tuff (LCB) provide a base for comparing unidentified tephra using Rare-Earth Elements. Samples KS-47, KS-49, and KS-50 have been identified as outcrops of LCB and are shown as averaged values on the plot. Samples KS-1, -4, -11, -15, -16,-16A, -17, -17A, -19, -20, -23, -26, -27, -31, -39, and KS-46 are known as the Pearlette Ash (Izett and Wilcox, 1982). Pearlette Ash samples and the previously identified outcrops of LCB suggest a highly correlative relationship based on REE chemistry. Naeser et al., 1973 identified KS-47, Izett and Wilcox, 1982 identified KS-49 and KS-50, and Westgate et al. 1994 identified UA 256.

Figure 15 plots the REE of the Pearlette Ashes and the unpublished samples (BTD-KS) collected during this study against the Lava Creek B Tuffs. With the exception of the Pearlette samples KS-58 and KS-76 little variability is seen between the undifferentiated ashes and the Lava Creek B Tuffs. The most variability can be seen among the Eu anomaly, but variation is minimal.

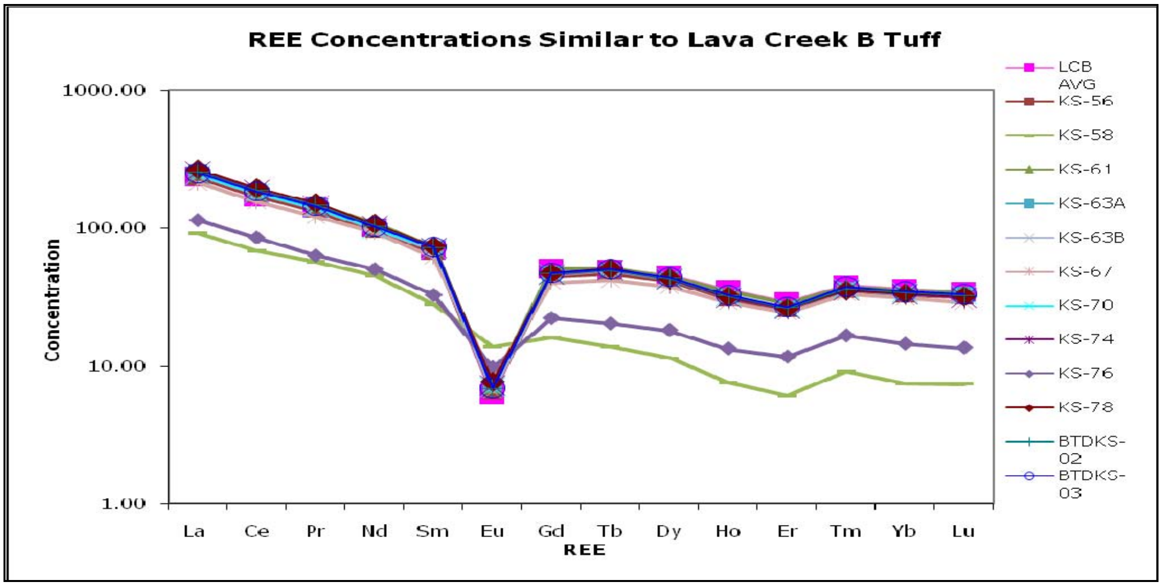

Figure 15. Previously dated outcrops of Lava Creek B Tuff (KS-47, KS-49, and KS-50) provide a base for comparing undifferentiated tephra using Rare-Earth Elements. These samples are displayed as an avearge value on the plot. Samples KS-56, -58, -61, -63A, -63B, -67, -70, -74,-76, and -78 are known as Pearlette Ash (Izett and Wilcox, 1982). Samples BTD-KS-02 and BTD-KS-03 are unpublished samples discovered during the course of this study. The Pearlette Ash samples, unpublished samples, and the previously identified outcrops of LCB are correlative based on REE chemistry. However, KS- 58 and -76 do not have a similar pattern and thus are most likely not related with the Lava Creek B or other Tuffs from Yellowstone.

In Figure 16, 4 sets of undifferentiated ashes are plotted against the known eruptions from Yellowstone region that are used in this study using Ba/Rb Vs Sr/Rb ratios. In this plot the known Huckleberry and Lava Creek B Tuffs are plotted as averaged value in order to clean up the appearance of the graphs. As noted from the graphs most of the undifferentiated Pearlette Ashes have very similar values with the averaged Lava Creek B Tuffs. The exception would be the Pearlette sample KS-58 and KS-76 which don't plot with ashes from the Yellowstone region. The three Pliocene ash samples (ADA-23, -24, and -28) share very similar values with the averaged Huckleberry Ridge Tuffs. ADA-25 does not appear to plot with any tuffs from the Yellowstone region. Since only one sample of the Mesa Falls Tuff was used this may not be a reliable indicator of the trace element geochemistry of the Mesa Falls Tuff. However, this value consistently plots in different regions of the graphs than does the averaged Huckleberry Ridge and Lava Creek B Tuffs. The unpublished ash sample (RD-CL) from Van Fleet, 1999 plots in the same region as the averaged Huckleberry Ridge Tuffs. The other two samples RD-LA and RD-NL do not align with the tuffs from the Yellowstone region.

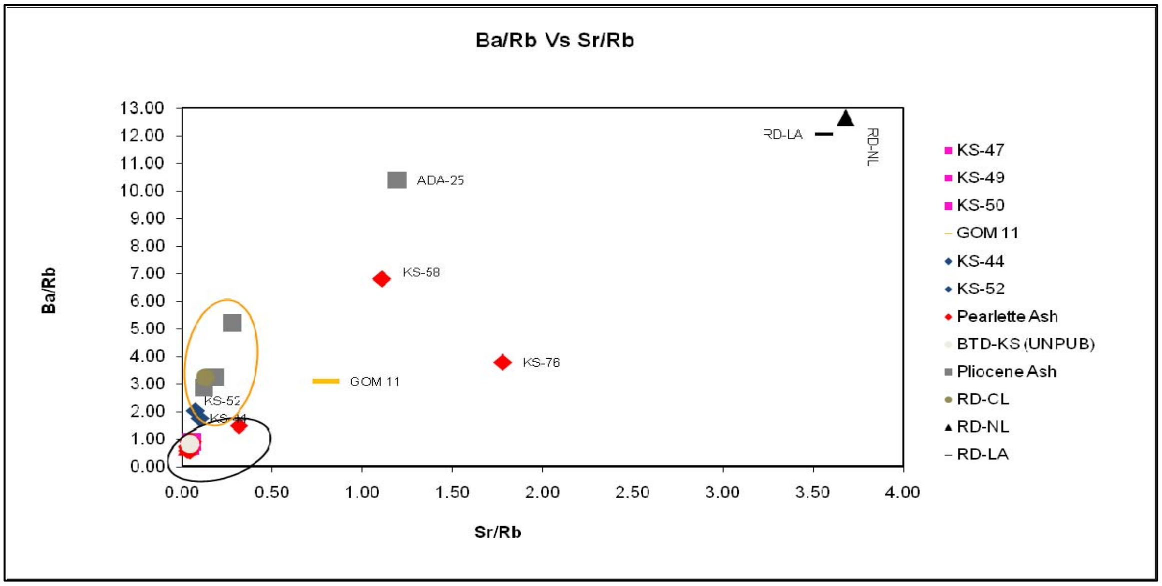

Figure 16. Ba/Rb Vs Sr/Rb ratio of the Pearlette, Pliocene, unpublished ash found in this study, and unpublished ash from Van Fleet, 1999 plotted against the average known Lava Creek B (KS- 47, 49, and -50, and UA 256) and Huckleberry Ridge Tuffs (KS-44 and KS-52, and UA 598). The Mesa Falls Tuff (MFT) is a single value entity. The Ba/Rb Vs Sr/Rb ratios clearly help to differentiate between the unkown samples and Yellowstone tuffs.

In Figure 17 the known eruptions from Yellowstone region are plotted against the 4 sets of undifferentiated ashes used in this study using Zr/Rb Vs Sr/Rb ratios. The known Huckleberry and Lava Creek B Tuffs are plotted as averaged value to clean up the appearance of the graphs. Most of the undifferentiated Pearlette Ashes have similar values with the averaged Lava Creek B Tuffs. The Pearlette Ash sample KS-58 and KS-76 do not plot with ashes from the Yellowstone region. The averaged Huckleberry Ridge Tuffs share very similar values with three Pliocene ash samples (ADA-23, -24, and -28) and one unpublished ash sample (RD-CL) from Van Fleet, 1999. Pliocene sample ADA-25 and the two unpublished samples (RD-NL and RD-LA) from Van Fleet, 1999 appear not to correlate with any tuffs from the Yellowstone region.

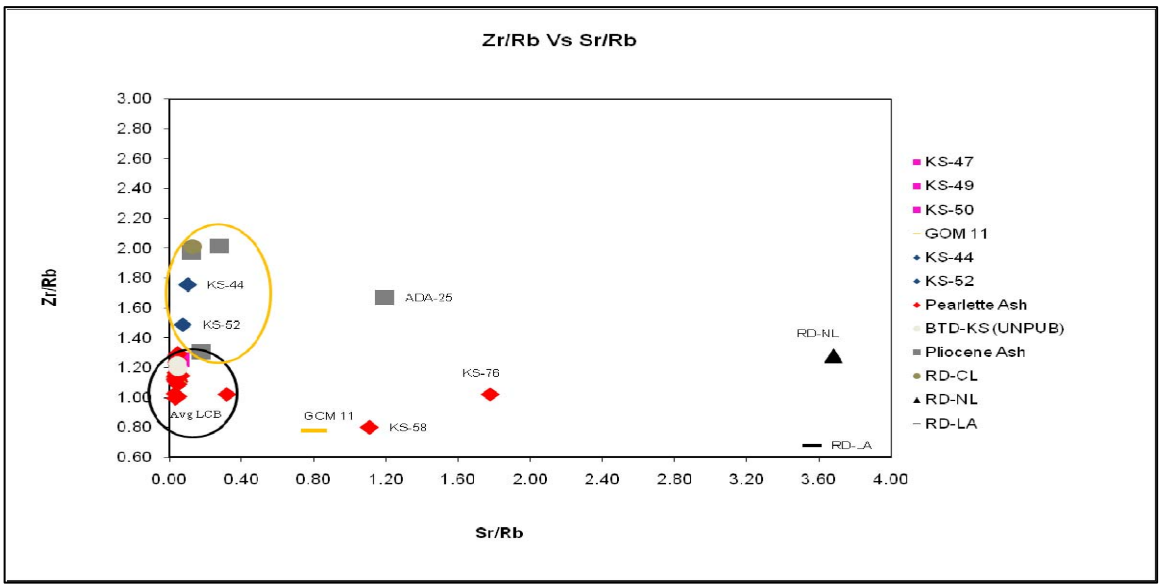

Figure 17. Zr/Rb Vs Sr/Rb ratio plot for all of the unknown samples used in this study and plotted against the averages of the known Lava Creek B Tuffs (KS- 47, 49, and -50, and UA 256) and Huckleberry Ridge Tuffs (KS-44 and KS-52, and UA 598). The Mesa Falls Tuff was not aveараged since only one sample was present. These ratios clearly support the notion that tuffs with a similar trace element chemistry can be seggregated using trace elements.

In Figure 18 the known eruptions from the Yellowstone region are plotted against the 4 sets of undifferentiated ashes used in this study using the ratios of La/Lu Vs Eu anomaly. In order to clean up the appearance of the graphs the known Huckleberry and Lava Creek B Tuffs are plotted as averaged values. The scales of the x- and y-axis used on this graph to display all of the unknown ash samples give the appearance that Huckleberry Ridge cluster near the Lava Creek B Tuffs and that there is wide spread scatter seen among the Huckleberry Ridge Tuffs. However, when the outliers are removed this scatter dissipates. Most of the undifferentiated Pearlette Ashes have similar values with the averaged Lava Creek B Tuffs. The Pearlette Ash sample KS-58 and KS-76 do not plot with ashes from the Yellowstone region. Three Pliocene ash samples (ADA-23, -24, and -28) appear to have more scatter than what is seen when using Ba/Rb Vs Sr/Rb ratios and the one unpublished ash sample (RD-CL) from Van Fleet, 1999. Pliocene sample ADA-25 and two unpublished samples (RD-NL and RD-LA) from Van Fleet, 1999 appear not to correlate with any tuffs from the Yellowstone region. One sample of the Mesa Falls Tuff was used and may not be a reliable indicator of the trace element geochemistry for the Mesa Falls Tuff.

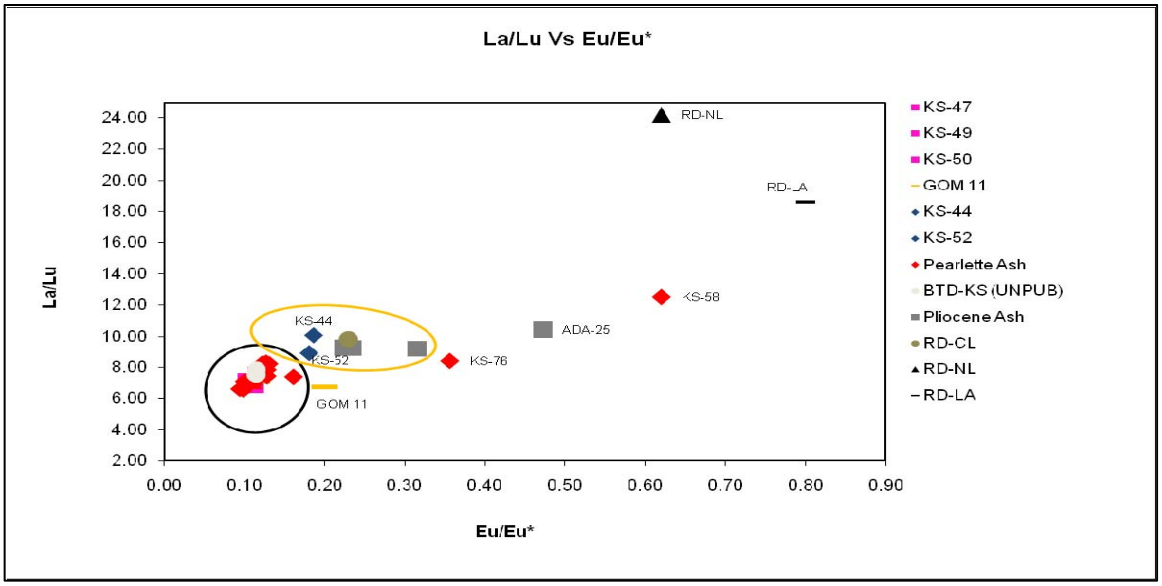

Figure 18. All the unknown ash samples collected in this study are plotted using La/Lu Vs Eu/Eu* and are are compared with average values of the Lava Creek B Tuffs (KS-47, -49, -50, and UA 256) and Huckleberry Ridge Tuffs (KS-44, KS-52, and UA 598). Mesa Falls Tuff (MFT) is a single ash sample. Using La/Lu Vs Eu/Eu* ratios help in correlating undifferentiated ashes.

In Figure 19 the 4 sets of undifferentiated ashes are plotted against the known eruptions from Yellowstone region that are used in this study using La/Sm Vs Eu anomaly. In order to clean up the appearance of this plot the Huckleberry and Lava Creek B Tuffs are plotted as averaged values. As noted from the graphs most of the undifferentiated Pearlette Ashes share very similar values with the averaged Lava Creek B Tuffs. The exception would be the Pearlette sample KS-58 and KS-76 which don't plot with the ashes from the Yellowstone region. There are three Pliocene ash samples (ADA-23, -24, and -28) that appear to group with Huckleberry Ridge Tuff—except these ashes appear to have higher values. ADA-25 does not appear to plot with any tuffs from the Yellowstone region. Since only one sample of the Mesa Falls Tuff was used this may not be a true indicator of the trace element geochemistry of the Mesa Falls Tuff. The Mesa Falls Tuff value plotted in the same region as the averaged Huckleberry Ridge, Pliocene (ADA-23, -24, and -28), and Van Fleet's (1999) unpublished sample RD-CL. The other two samples RD-LA and RD-NL do not align with the tuffs from the Yellowstone region.

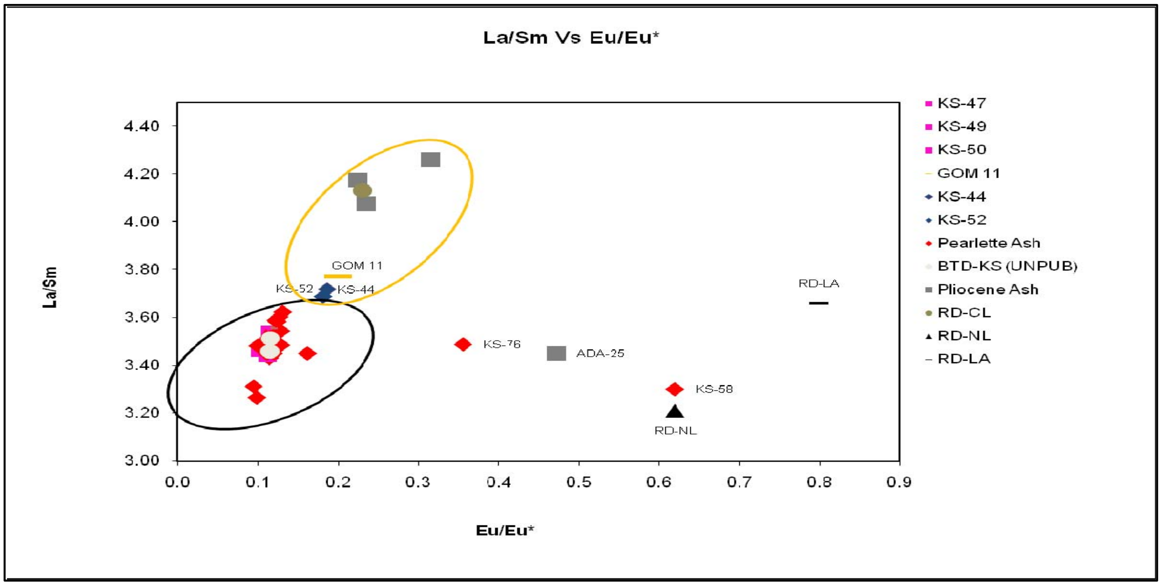

Figure 19. All the unknown ash samples collected for this study were plotted using La/Sm Vs Eu/Eu* and are are compared the averaged Lava Creek B Tuffs (KS-47, -49, -50, and UA 256) and Huckleberry Ridge Tuffs (KS-44, KS-52, and UA 598). Along with a single sample of Mesa Falls Tuff (MFT). In showing the fraction of the light Rare-Earths it becomes clear that using these ratios could definitely aid in fingerprinting undifferentiated tephra's.

A spider plot was constructed between the known averaged Lava Creek B Tuffs used in this study and the listed Pearlette Ashes seen in Figure 20. Slight variation can be seen in the more mobile elements like Sr, Rb, and Ba, however, this is a miniscule amount of variation. In the less mobile elements the variation seen between the Lava Creek B and the Pearlette Ashes is practically null.

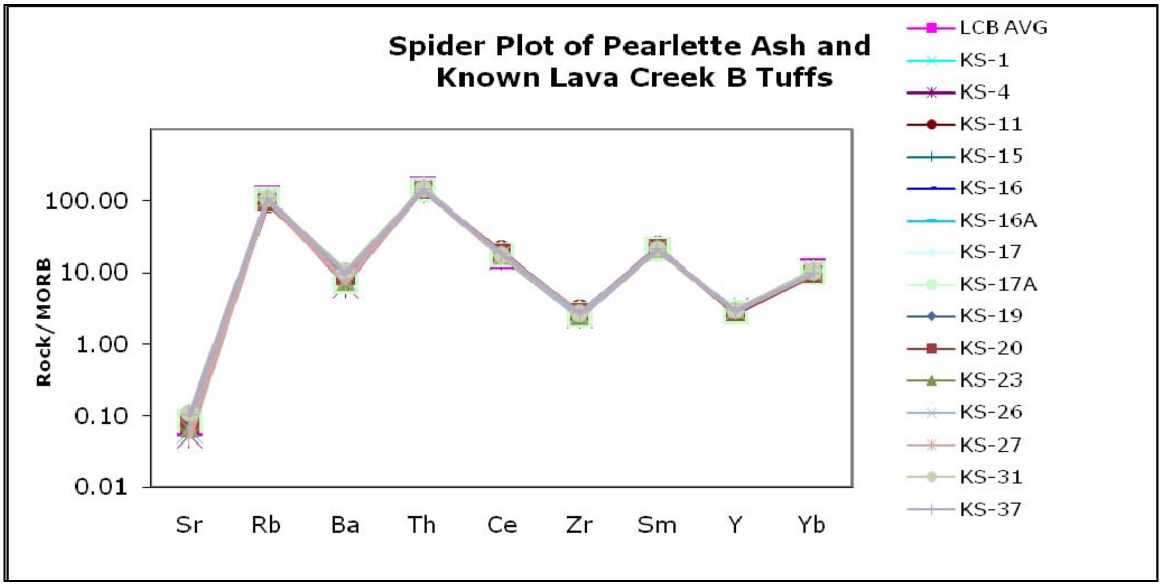

Figure 20. Spider plot for the published Lava Creek B Tuffs and the listed Pearlette Ashes found in Kansas. Overall, there is minimal variablity seen in the spider diagram and this suggests that the listed Pearlette Ashes and the Lava Creek B Tuffs are genetically related. Elements normalized to MORB based on standards of Pearce, 1983.

The spider plot seen in Figure 21 is between known Lava Creek B Tuffs, Pearlette Ashes, and the BTD-KS samples. From this graph it can be clearly seen that the Pearlette and BTD-KS samples correlate with the Lava Creek B. There is an exception which is KS-58 and KS-76 which do not correlate with any tuff from the Yellowstone region. These plots show little variation among the mobile and less mobile elements.

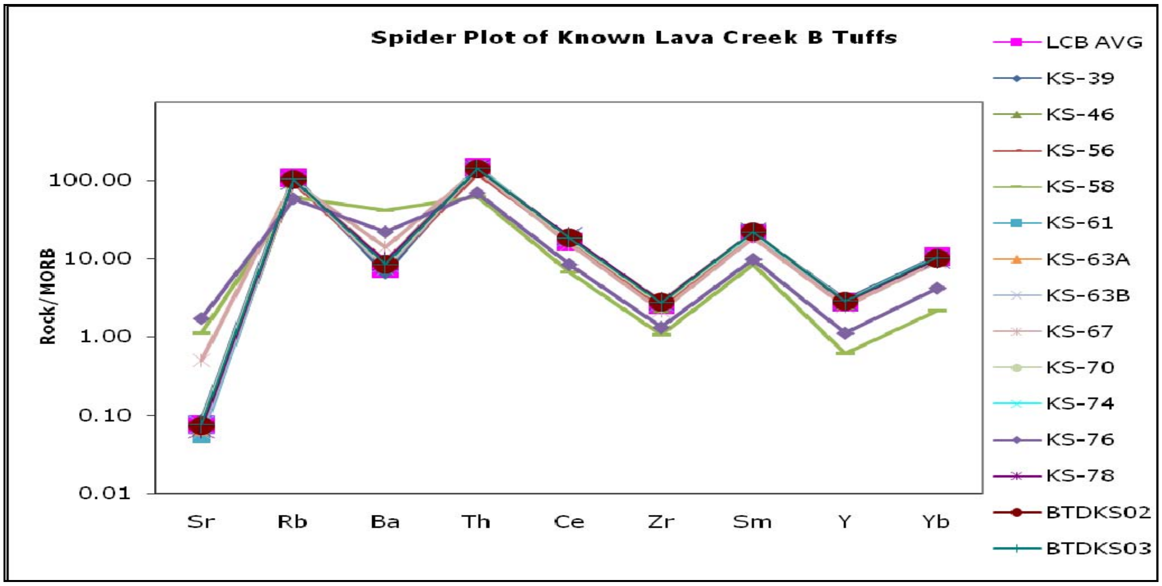

Figure 21. Spider plot shows minimal variation among the mobile and less mobile elements between the published Lava Creek B Tuffs and the above listed Pearlette Ashes found in Kansas. This strongly suggests that a correlation exists between Pearlette Ashes and Lava Creek B Tuffs. Pearlette Ash samples KS-56 and -78 show a great amount of variability amoung the graphs. Elements normalized to MORB based on the standards of Pearce, 1983.

Pliocene Ashes of Kansas

In total, 4 Pliocene Ashes from Swineford et al. 1955 were analyzed using Rare-Earth Elements (Figure 22), trace elements ratios (Figure 16-19), and Spider Diagrams (Figure 23). Three out of the 4 samples looked at in this study (ADA-23, -24, and -28) appear to match the Huckleberry Ridge Tuff from the Yellowstone Region**.** One Pliocene Ash (ADA-25) could not be confidently matched to any tuff from the Yellowstone Region (Figures 16-19 and 22-23). The Rare-Earth Element patterns, the trace element ratios and spider diagrams are all supporting evidence that these Pliocene Ashes do indeed correlate with the Huckleberry Ridge Tuffs.

The REE plots for the Huckleberry Ridge Tuffs and the undifferentiated samples suspected of being genetically related are shown in Figure 22. Clearly the Pliocene samples marked as ADA-23, -24, and -28 are very similar in REE chemistry to the Huckleberry Ridge Tuffs as is the sample RD-CL. Samples ADA-25, RD-NL, and RD-CL show to much variation to be related to the Huckleberry Ridge Tuffs.

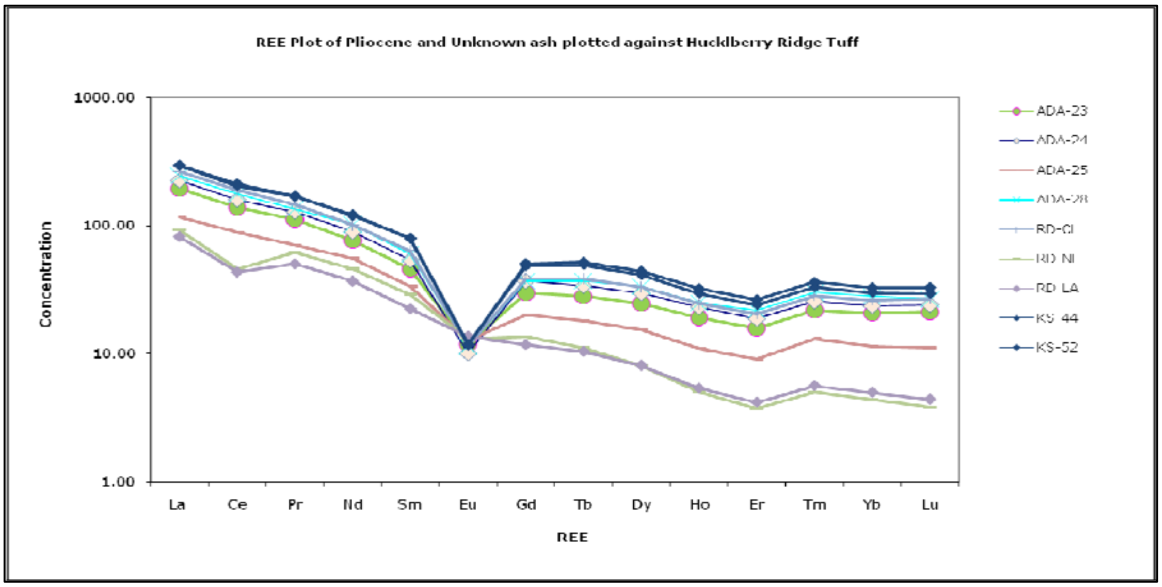

Figure 22. Overall trend of Rare-Earth Element seen in Pliocene tuff's from Swineford et al. (1955). ADA-23 is a Dellvale Ash Bed, ADA-24 is called Calvert Ash Bed, ADA-25 was named Reager Ash Bed, and ADA-28 was named Reamsville Ash Bed. However, this study shows that ADA-23, -24, -28, and RD-CL are genetically similar to Huckleberry Ridge Tuff from the Yellowstone Volcanic Field. ADA-25, RD-NL, and RD-LA do not correlate with any tuff from the Yellowstone region.

The spider plots of the suspected ashes thought to be related to the Huckleberry Ridge Tuffs are shown in Figure 23. Three samples ADA-25, RD-NL, and RD-LA do not appear to be genetically related with the Huckleberry Ridge Tuffs. Samples ADA-23, -24, -28, and RD-CL appear to be related with the Huckleberry Ridge Tuff. Little variation can be seen between the mobile and immobile elements.

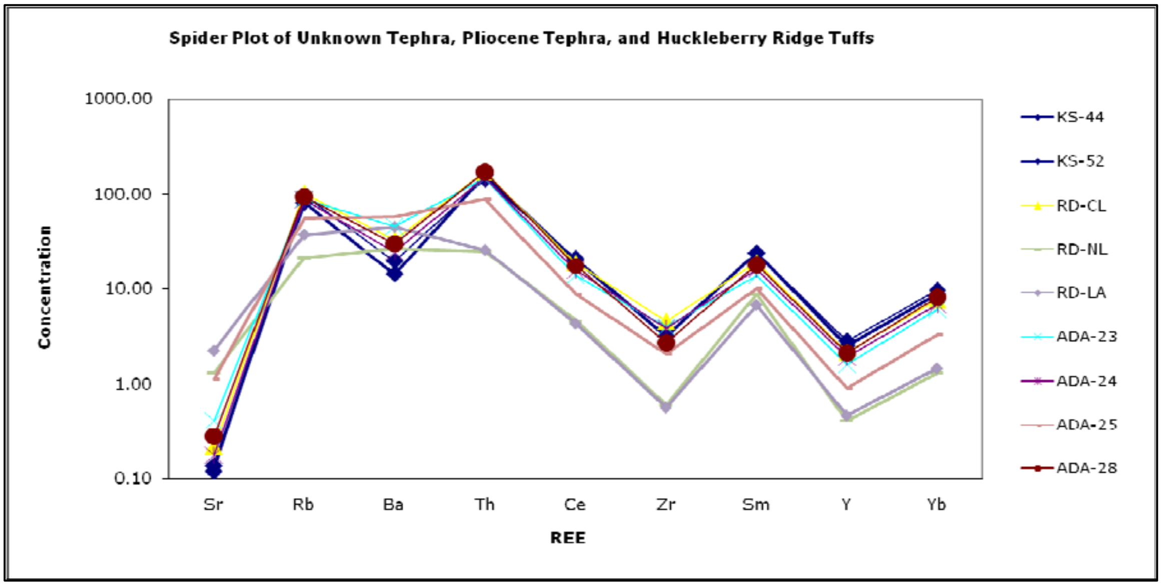

Figure 23. Spider plot for the Huckleberry Ridge Tuff—i.e., the previously published samples,the Pliocene Ashes and the previsously unpublished ashes from Van Fleet, 1999 found in Kansas. The more mobile elements like Sr, Rb, and Ba show the greatest variablity and could be the result of magmatic differentiation. In the least mobile elements like Th, Ce, zr, Sm, Y, and Yb there is little variation seen among the different tuffs. Elements are normalized to MORB standards of Pearce, 1983.

Unpublished Ash Samples

In total, 3 unpublished ashes from Van Fleet, 1999 were analyzed using Rare-Earth Elements (Figure 22) and trace elements ratios (Figures 16-19). One out of the 3 samples (RD-CL) appears to correlate with the Huckleberry Ridge Tuff from the Yellowstone Plateau Volcanic Field**.** The 2 remaining unpublished ash samples (RD-NL and RD-LA) could not be correlated to a tuff from the Yellowstone region (Figures16-19and 22-23). The Rare-Earth Element patterns, the trace element ratios and spider diagrams are all supporting evidence that the Pliocene Ash RD-CL correlates with the Huckleberry Ridge Tuff.

Chapter 6 Conclusion

A detailed geochemical study was conducted on ash units found in Kansas to determine if trace elements could be a viable option to chemically “fingerprint” these units to known eruptions. Kansas is an ideal location to test this hypothesis for two main reasons: 1) most of the source for the ashes is believed to be derived from one region-i.e., Yellowstone region, and 2) there are a substantial number of ashes that are undifferentiated and simply described as the “Pearlette Ash” in the literature.

The Lava Creek B, Mesa Falls, and Huckleberry Ridge Tuffs from the Yellowstone region have distinct trace element and REE signatures. Comparison of these signatures with the ash units of unknown origin may be used to correlate them to specific eruptions. It was determined that using the trace element ratios of Ba/Rb, Sr/Rb, Zr/Rb, La/Lu, La/Sm, and Eu/Eu* (Europium anomaly) were useful in separating eruptions that have similar overall trace element chemistry.

A majority (25/29) of the Pearlette Ash samples appear to correlate very well to the Lava Creek B Tuff. The following Pearlette Ashes correlated to the Lava Creek B Tuff: KS-1, KS-4, KS-11, KS-15, KS-16, KS-16A, KS-17, KS-17A, KS-19, KS-20, KS-23, KS-26, KS-27, KS-31, KS-37, KS-39, KS-46, KS-56, KS-61, KS-63A, KS-63B, KS-67, KS-70, KS-74, and KS-78. The remaining 2 Pearlette Ashes (KS-58 and KS-76) could not be matched confidently to any tuff from the Yellowstone Region. Pearlette Ashes KS-45A and KS-45B yielded insufficient glass to do a chemical analysis.

During the course of this study 3 unpublished ash samples were collected and informally named BTD-KS-01, -02, -03. BTD-KS-01 did not yield enough glass to conduct a quantitative chemistry analysis. The remaining two samples BTD-KS-02 and -03 appear to correlate very well with the Lava Creek B Tuff.

The majority (3/4) of the ash samples reported to be Pliocene by Swineford et al., 1955 appear to correlate with the Huckleberry Ridge Tuff. The ash samples that appears to be Huckleberry Ridge are the ADA-23, -24, and -28. ADA-25 does not appear to correlate with any tuff from the Yellowstone region.

Van Fleet, 1999 collected 3 ash samples from Norton, Calvert, and Almena Counties in Kansas. He informally named these samples RD-NL, RD-CL, and RD-LA after each county they were collected from. Using trace element geochemistry only one of these samples (RD-CL) appears to match the Huckleberry Ridge Tuff. The remaining two samples RD-NL and RD-LA do not appear to match with any tuff from the Yellowstone region.

In conclusion, this study proves the utility of using trace elements to correlate undifferentiated ashes with ashes of known eruptions. One major hindrance to this study is the lack of published trace element data of glass from known eruptions available for comparison. Future work on these Kansas ash outcrops should include determining the absolute ages, obtaining major element chemistry, and a detailed sedimentological study to determine depositional environment. This future work would remove any doubt about the origin of these undifferentiated samples found in Kansas.

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WWW.esri.com, Kansas map with county outlines.

Appendix 1 Tables of Raw Trace Element Concentrations

Table A1.1. Rare-Earth Element (REE) raw analysis of glass shards using inductively coupled plasma--mass spectrometry (ICP-MS) measured in ppm.

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
KS-1	81.13	154.09	16.78	65.08	13.49	0.48	12.86	2.30	13.06	2.63	7.73	1.17	7.49	1.11
KS-4	77.55	149.71	16.15	62.75	13.43	0.41	13.01	2.38	13.70	2.76	8.17	1.27	8.05	1.17
KS-11	86.62	170.75	17.74	66.49	14.07	0.53	12.08	2.36	13.02	2.50	7.43	1.15	7.49	1.11
KS-15	81.06	159.46	16.63	62.50	13.45	0.47	11.99	2.27	12.94	2.51	7.28	1.17	7.55	1.12
KS-16	87.92	170.50	18.07	67.43	14.23	0.56	12.21	2.38	12.97	2.50	7.35	1.18	7.38	1.12
KS-16A	79.66	157.01	16.35	61.53	13.06	0.49	11.60	2.22	12.52	2.44	7.10	1.13	7.25	1.09
KS-17	87.37	169.24	17.85	66.78	14.21	0.53	12.40	2.40	13.15	2.56	7.62	1.20	7.57	1.13
KS-17A	81.76	160.58	16.77	62.87	13.53	0.46	11.90	2.34	12.89	2.51	7.42	1.18	7.51	1.11
KS-19	84.38	164.83	17.20	64.65	13.76	0.49	12.07	2.35	12.90	2.51	7.49	1.17	7.43	1.12
KS-20	87.95	170.21	17.98	66.76	13.92	0.56	11.86	2.27	12.47	2.37	7.06	1.12	7.04	1.07
KS-23	82.64	158.68	16.62	67.21	13.82	0.49	12.02	2.32	13.52	2.66	8.14	1.26	8.09	1.16
KS-26	83.62	162.75	17.20	66.54	13.77	0.44	13.00	2.38	13.46	2.73	8.03	1.23	7.84	1.18
KS-27	81.09	155.75	17.17	64.39	13.20	0.47	12.97	2.27	13.14	2.63	7.69	1.18	7.51	1.14
KS-31	85.46	160.82	17.60	67.90	13.97	0.55	12.99	2.38	13.33	2.72	8.05	1.23	7.83	1.16
KS-37	84.07	164.67	17.42	64.79	13.84	0.55	12.13	2.33	12.94	2.50	7.44	1.19	7.46	1.13
KS-39	77.81	153.81	16.24	60.84	13.67	0.42	12.10	2.45	13.63	2.64	7.88	1.25	7.99	1.19
KS-44	100.68	185.41	20.68	77.48	15.53	0.87	12.58	2.32	12.33	2.30	6.72	1.06	6.59	1.00
KS-46	84.16	164.70	17.21	64.70	13.48	0.52	11.90	2.25	12.60	2.44	7.14	1.15	7.17	1.08
KS-47	82.16	157.82	17.10	66.28	13.68	0.49	12.96	2.39	13.55	2.77	8.05	1.24	7.95	1.20
KS-49	86.96	160.69	18.02	69.14	14.11	0.52	13.21	2.35	13.25	2.70	7.79	1.21	7.68	1.16
KS-50	81.62	155.84	16.80	65.15	13.52	0.45	13.09	2.34	13.34	2.72	7.88	1.21	7.73	1.15
KS-52	99.88	192.22	20.34	76.66	15.53	0.86	13.14	2.43	13.20	2.52	7.39	1.16	7.22	1.12
KS-56	78.91	155.43	16.19	60.82	12.94	0.47	11.48	2.18	12.41	2.40	7.05	1.12	7.13	1.07
KS-58	31.21	62.21	6.91	28.93	5.43	1.00	4.19	0.65	3.40	0.59	1.69	0.29	1.63	0.25
KS-61	87.25	164.05	17.91	69.40	14.07	0.52	13.17	2.38	13.29	2.71	7.91	1.20	7.74	1.17

Table A1.1. Rare-Earth Element (REE) raw analysis of glass shards using inductively coupled plasma--mass spectrometry (ICP-MS) measured in ppm.

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
KS-63A	87.43	169.29	17.90	66.57	13.98	0.53	12.28	2.33	12.79	2.47	7.37	1.15	7.31	1.12
KS-63B	82.26	162.35	16.91	63.69	13.64	0.48	11.90	2.34	12.84	2.52	7.38	1.15	7.52	1.11
KS-67	72.35	141.12	14.60	59.66	12.03	0.60	10.43	1.97	11.26	2.24	6.80	1.07	6.83	0.98
KS-70	82.40	162.35	16.94	63.80	13.70	0.51	12.10	2.33	13.00	2.52	7.38	1.17	7.51	1.12
KS-74	88.01	172.05	17.83	66.91	14.07	0.53	12.02	2.35	12.79	2.46	7.26	1.13	7.36	1.07
KS-76	38.62	77.30	7.62	32.06	6.35	0.71	5.76	0.95	5.43	1.04	3.24	0.53	3.17	0.46
KS-78	90.50	176.92	18.41	69.06	14.41	0.56	12.27	2.39	13.00	2.49	7.34	1.13	7.38	1.09
ADA-23	66.10	126.51	13.45	48.89	8.90	0.87	7.79	1.32	7.45	1.49	4.41	0.70	4.58	0.72
ADA-24	76.09	144.20	15.47	57.37	10.45	0.74	9.58	1.59	8.93	1.80	5.23	0.82	5.19	0.82
ADA-25	39.71	80.94	8.52	35.36	6.60	0.93	5.24	0.85	4.64	0.85	2.53	0.42	2.50	0.38
ADA-28	83.08	159.93	16.31	64.82	11.69	0.83	9.63	1.74	9.99	1.95	6.07	0.96	6.15	0.90
RD-NL	31.42	41.82	7.43	29.25	5.62	0.95	3.56	0.52	2.43	0.39	1.04	0.16	0.97	0.13
RD-CL	89.37	171.55	17.68	64.62	12.41	0.85	9.95	1.81	9.92	1.92	5.70	0.91	5.77	0.91
RD-LA	27.85	39.46	6.07	23.55	4.37	1.00	3.06	0.49	2.44	0.42	1.17	0.18	1.10	0.15
BTDKS02	86.36	170.16	17.64	66.26	14.10	0.50	12.13	2.32	12.99	2.51	7.33	1.16	7.55	1.10
BTDKS03	84.86	167.78	17.43	65.45	14.07	0.50	12.25	2.35	13.18	2.55	7.47	1.19	7.66	1.13

Table A1.2 Published raw Rare-Earth Element (REE) analysis of glass shards for the Huckleberry Ridge (UA 598), Mesa Falls (GOM 11), and Lava Creek B (UA 256) Tuffs. The data was obtained from Westgate et al., 1994 and Jones 2008.

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
UA 256	70.00	138.00	15.70	56.00	12.40	0.36	13.27	2.27	14.20	2.95	8.60	1.28	8.21	1.16
UA 598	89.00	172.00	19.20	71.00	13.90	0.85	14.21	2.27	13.54	2.67	7.78	1.17	7.38	1.07
GOM 11	70.90	131.00	12.50	50.30	10.80	0.69	9.90	1.97	11.70	2.19	6.72	1.30	7.10	1.05

Table A1.3. Chondrite standards of Wakita et al., 1971 used to normalize Rare Earth Elements (REE).

La = 0.34	Eu = 0.073	Er = 0.279
Ce = 0.91	Gd = 0.26	Tm = 0.032
Pr = 0.12	Tb = 0.047	Yb = 0.22
Nd = 0.64	Dy = 0.30	Lu = 0.034
Sm = 0.195	Ho = 0.078	

Table A1.4. Normalizing standards of Pearce (1983) used to normalize the spider diagrams to a MORB.

Sr	120.00
Rb	2.00
Ba	20.00
Th	0.20
Ce	10.00
Zr	90.00
Sm	3.30
Y	30.00
YB	3.40

Appendix 2 Location, Description and Pictures of Tephra Samples

Site Locations and Descriptions

Sample numbers marked with an asterisk (*) were obtained in a study from Van Fleet (1999). Location, descriptions, and pictures of these samples are based on Van fleet's field work. Sample numbers marked with a double asterisk (**) were provided by Totten, M.W., unpublished work.

This study used the same naming scheme as used by Izett and Wilcox, 1982, unless samples were previously undescribed in the literature or were part of a previous study—e.g., Swineford et al. 1955. Swineford samples are identified as ADA and samples that are previously undescribed in literature start with BTD-KS. Samples starting with RD-NL, RD-CL, and RD-LA are from Van Fleet 1999, unpublished work.

GPS markings are based on the North American Datum (NAD) 83. Color description is based on the Munsell Rock Color Chart. The following tephra samples could not be located in the field —KS-12, KS-13, KS-18, KS-35, KS-36, KS-38, KS-40, KS-42, KS-43, KS -45B, KS-45C, KS-54, KS-79, KS-81A, and KS-81B see Figure 3 for locations.

KS-1*: Location—Chautauqua County, KS approximately 3.00 KM north of the city of Peru. Township and Range—NW ¼ NW ¼ SE ¼ Sec. 9, T. 34 S., R. 12 E. Global Positioning System (GPS) location—N 37.00° 04.03 and W 96.00° 04.07.

Tephra sample is exposed on the west side of a north-south road in an approximately 1.00 meter wide band with an undetermined depth. Outcrop is small, and blends into the surrounding reddish-soil. Fresher tephra samples were obtained by digging to a depth of approximately 20.00 cm (Figure A2.1).

KS-4*: Location—Clark County, KS. Township and Range—SE ¼ SE ¼ Sect. 23, T. 30 S., R 24 W. GPS location—N 37.00° 24.79 and W 99.00° 54.33.

Outcrop of tephra is located in a stream-cut with a buff colored cliff approximately 2.00 meters above the ash (Figure A2.2).

KS-11: Location—Ellis County, KS. Township and Range—SE ¼ SE ¼ Sect. 17., T 14 S., R 19 W. GPS location—N 38.00° 49.00' 40.80" and W 99.00° 27.00' 6.00".

Tephra sample is white (N9) and is approximately 1.00 meter thick. It is located along a creek bank and hard to place in a stratigraphic sequence. Possibly an old flood deposit (Figure A2.3).

KS-12: Location—Ellsworth County, KS. Township and Range—N ½ SW ¼ Sec. 22, T. 15 S., R. 7 W.

KS-12 sample could not be located in the field.

KS-13: Location—Ellsworth County, KS. Township and Range—SE ¼ NW ¼ Sec. 28, T.16 S., R. 7 W.

KS-13 sample could not be located in the field.

KS-15: Location—Gove County, KS. Township and Range—NE ¼ SW ¼ Sect. 21, T. 13 S., R. 26 W. GPS location—N 38.00° 54.00' 21.60" and W 100.00° 13.00' 13.80".

Tephra is white (N9) and is approximately 2.00~3.00 meters thick by 40.00 meters long and is found in an abandoned pit-mine. Immediately above the tephra outcrop is an approximately 1.50 meter very pale-orange (10 YR 8/2) siltstone. This siltstone grades into a 0.25 meter weathered conglomerate with well-rounded to sub-angular igneous clasts that range in size from 0.20 cm up to 3.00 cm (Figure A2.4).

KS-16: Location—Gove County, KS. Township and Range—SW ¼ SE ¼ Sect. 25, T 15 S., R 28 W. GPS location—N 38.00° 43.00' 01.70" and W 100.00° 22.00' 51.80".

Tephra is a very light-gray (N8) and ranges in thickness from 0.25 to 1.00 meter. The tephra overlies silt that is yellowish-gray (5 Y 8/1) and is mixed with well-rounded to sub-angular igneous clasts that range from 0.20 cm to 3.00 cm. Tephra ranges from an impure mixture of ash and silt to a relatively pure ash. The tephra is well-indurated and forms a competent bed that has a strike of N 50 E and a dip of 20°. Sequence of the outcrop consists of a basal light-gray (N6) to medium-gray (N5) shale unit, yellowish-gray (5 Y 8/1) silt, and tephra (A2.5). Also noted in the outcrop was a second tephra unit located approximately 5.00 meters up-section (Figure A2.6). This tephra unit was named KS-16A.

KS-16A: Location—Gove County, KS. Township and Range—SW ¼ SE ¼ Sect. 25, T 15 S., R 28 W. GPS location—N 38.00° 43.00' 01.70" and W 100.00° 22.00' 51.80".

Tephra is a very light-gray (N8) and ranges in thickness from 0.25 to 0.50 meter. This tephra is located approximately 5.00 meters above a lower tephra unit (KS-16). The sedimentary rock that separates KS-16A from KS-16 is a yellowish-gray (5 Y 8/1) silt that grades into a weathered conglomerate consisting of well-rounded to sub-angular igneous clasts ranging from 0.20 cm to 3.00 cm. Sequence of the outcrop consists of a basal light-gray (N6) to medium-gray (N5) shale unit, yellowish-gray (5 Y 8/1) silt, lower tephra (KS-16), an intermediate yellowish-gray (5 Y 8/1) siltstone (approximately 5.00 meters), weathered conglomerate, and an upper tephra (KS-16A) (Figure A2.6).

KS-17: Location—Gove County, KS. Township and Range—Center NE ¼ Sect. 14, T. 15 S., R 28 W. GPS location—38.00° 45.00’ 12.50” and W 100.00° 23.00’ 40.90”.

Tephra is white (N9) and approximately 1.00~2.00 meters high by 60.00 meters long, is very clean and pure, and overlies a chalk unit. Immediately above the ash in a conformable sequence is what appears to be an approximately 2.00 cm to 3.00 cm medium light-gray (N6) to medium-gray (N5) lacustrine limestone. Present on the limestone is what appears to be ripple marks. Above this limestone is a very pale-orange (10 Y/R 8/2) siltstone that grades into a second tephra unit (KS-17A). This second tephra is approximately 1.00~2.00 meters above the lower tephra (KS-17). Conformable to the tephra is a weathered yellowish-gray (5 Y 8/1) conglomerate with igneous clasts that range in size from 0.20 cm to 3.00 cm (Figure A2.7 and Figure A2.8).

KS-17A: Location—Gove County, KS. Township and Range—Center NE ¼ Sect. 14, T. 15 S., R 28 W. GPS location—38.00° 45.00’ 12.50” and W 100.00° 23.00’ 40.90”. Tephra is white (N9) and approximately 0.50 meters thick and ranges from silty to a relatively clean tephra sample. See KS-17 for explanation of outcrop (Figure A2.7).

KS-18: Location—Gove County, KS. Township and Range—SW ¼ NW ¼ Sec. 17, T. 15 S., R. 27 W.

KS-18 sample could not be located in the field.

KS-19: Location—Gove County, KS. Township and Range—E ½ NW ¼ Sec. 33, T. 15 S., R. 27 W. GPS location—N 38.00° 42.00’ 36.80” and W 100.00° 19.00’ 56.00”.

Tephra is white (N9) is approximately 1.00 meter and is relatively clean tephra sample. Outcrop consist of a basal grayish-yellow (5 Y 8/4) chalk. The overlying 1.00 meter yellow-gray (5Y 8/1) silt forms an abrupt contact with the underlying chalk. Also noted was the presence of small igneous clasts ranging from 0.20 cm up to 1.00 cm (Figure A2.9).

KS-20: Location—Gove County, KS. Township and Range—NW ¼ NE ¼ Sec. 26, T. 15 S., R. 29 W. GPS location—N 38.00° 43.00’ 38.20” and W 100.00° 30.00’ 46.20”.

Tephra is white (N9) and is approximately 0.50 meter to ~1.00 meter by 20.00 meters long in a discontinuous outcrop. Tephra overlies a medium light-gray (N6) to medium-gray (N5) nonindurated shale member of the Mead Formation in this outcrop location (Izett and Wilcox, 1981). A very pale-orange (10 Y/R 8/2) silt that is approximately 1.00 meter separates the tephra from the Meade Formation. Igneous clasts ranging from 0.50 cm up to 1.00 cm were discovered in the siltstone (Figure A2.10).

KS-23*: Location—Grant County, KS. Township and Range—NW ¼ Sec. 24 T. 30 S., R. 35 W. GPS location—N 37.00° 25.84 and W 101.00° 06.17.

Tephra is located in a former commercial quarry and is approximately 5.00 meters thick. Noted in the ash are rip-up clasts of the underlying silt and sand bed. The upper tephra contains rip-up clasts of the overlying silt and sand beds (Figure A2.11).

KS-26*: Location—Harper County, KS. Township and Range—NE ¼ NE ¼ Sec. 29, T. 33 S., R. 6 W. GPS location—N 37.00° 09.12 and W 98.00° 01.68. GPS waypoint is for the Dairy Queen at the intersection of Highways 170 and 44; the tephra outcrop lies 3.00 Km east of this intersection.

Unable to locate the pit-mine the tephra was originally mined due to overgrowth of flora. A structure used during the active pit-mining operation was still standing. This structure contained tephra that was mined from the once existing pit-mine. Samples were obtained from this structure (Figure A2.12).

KS-27*: Location—Jewell County, KS. Township and Range—NW ¼ SE ¼ Sec. 32, T. 1 S., R. 9 W. GPS location—N 39.00° 55.22 and W 98.00° 21.15.

A very clean and pure 4.00 meter tephra outcrop was found in an abandoned pit-mine. The top of the tephra unit is mixed with a silty-sand. Also noted throughout the tephra were small-scale cross-beds (Figure A2.13).

KS-31*: Location—Jewell County, KS. Township and Range—Along Section Road line between Section 16 and 17, 6 kilometers north of the southern boundaries. T. 1 S., R. 6 W. GPS location—N 39.00° 57.66 and W 97.00° 59.75.

Fresh road-cut exposed a 1.00 meter thick tephra unit. This unit was overlain by approximately a 1.00 meter of soil**.** (Figure A2.14).

KS-35: Location—Logan County, KS. Township and Range—E ½ NE ¼ Sec. 17, T. 12 S., R. 36 W.

KS-35 sample could not be located in the field.

KS-36: Location—Logan County, KS. Township and Range—SW ¼ NW ¼ Sec. 36, T. 12 S., R. 36 W.

KS-36 sample could not be located in the field.

KS-37: Location—Logan County, KS. Township and Range—SW ¼ NW ¼ Sec. 12, T. 13 S., R. 35 W. GPS location—N 38.00° 56.00’ 28.80” and W 101.00° 10.00’ 0.90”.

A 0.50 meter thick tephra unit was discovered overlaying silt. The tephra is weathering to a grayish-yellow (5 Y 8/4) and a very pale-orange (10 YR 8/2). Fresh tephra reveals a white (N8) to light gray (N9). Tephra is indurated, pumiceous and contains approximately 3 % biotite. Also noted were abundant igneous litho-clasts (0.20 cm to 2.00 cm) and are well-rounded to sub-angular in the silt layer (Figure A2.15).

KS-38: Location—Logan County, KS. Township and Range—SE ¼ NW ¼ NW ¼ Sec. 2, T. 14 S., R. 33 W.

KS-38 sample could not be located in the field.

KS-39: Location—Logan County, KS. Township and Range—NE ¼ Sec. 34, T. 14 S., R. 33 W. is the Township and Range listed in Izett and Wilcox, 1981. Author found the out -crop at C ½ NE ¼ Sec. 34, T. 14 S. R. 33 W. GPS location—38.00° 47.00’ 48.00” and W 100.00° 58.00’ 19.30.”

Tephra outcrop is approximately 2.00 meter thick and 20.00 meter in lateral extent. The lower half of outcrop is buried and mixed with a yellowish-brown (10YR 6/2) silt. The tephra is overlain by 0.50 meter of a yellowish-brown (10YR 6/2) silt mixed with igneous clasts that range in size from 0.50 cm ~ 2.00 cm. Tephra is relatively clean and very-pumiceous. The outcrop is located on the eastern side of a small tributary stream valley (Figure A2.16).

KS-40: Location—Logan County, KS. Township and Range—SW ¼ SE ¼ SW ¼ Sec. 35, T. 13 S., R. 33 W.

KS-40 sample could not be located in the field.

KS-42: Location—Marshall County, KS. Township and Range—SE ¼ Sec. 9, T. 4 S., R. 9 E.

KS-42 sample could not be located in the field.

KS-43: Location—Marshall County, KS. Township and Range—Center South line Sec. 35, T. 2 S. R. 7 E.

KS-43 sample could not be located in the field.

KS-44: Location—McPherson County, KS. Township and Range—NE ¼ NE ¼ Sec. 14, T. 18 S., R. 3 W. GPS location—N 38.00° 29.00’ 24.30” and W 97.00° 36.00’ 43.00”.

Huckleberry Ridge Tuff outcrop is approximately 0.50 meter by 6.00 meters and is weathering to a very light-gray (N8) to white (N9). On the fresh surface the tephra is a pinkish-gray (5 Y/R 8/1). Biotite crystals (1.00 mm) appear to be oxidizing. The outcrop appears blocky and discontinuous, is located in a ravine that runs thru the private property of Mr. William Jones, 1683 Quivira Rd McPherson, KS. Gravel size tephra clumps are located on both sides of the ravine (Figure A2.17).

KS-45A: Location—McPherson County, KS. Township and Range—Along Section line Road between Sects. 15 and 16, T. 18 S., R. 4 W. GPS location—N 38.00° 29.00’ 21.60” and W 97.00° 45.00’ 26.10”.

Found pinkish-gray (5 Y/R 8/1) to white (N9) tephra interbedded with silt to clay size particles. Tephra forms very thin ~1.00 cm discontinuous beds throughout outcrop. Gravel size tephra clumps are weathering out of the silt. Tephra is very silty and impure and appears to be highly altered. Found ~1.00 mm biotite crystals in the tephra. Microscope evaluation reveals insignificant amounts of volcanic glass. Attempts to separate and clean this glass further supports the microscope work by yielding insignificant amounts of volcanic glass (Figure A2.18).

KS-45B: Location—McPherson County, KS. Township and Range—NW ¼ SW ¼ Sect. 15, T. 18 S., R. 4 W. GPS location—N 38.00° 29.00’ 03.10” and W 97.00° 44.00’ 58.50”.

Unable to locate an outcrop of tephra, however did located an outcrop that appeared to be very impure-tephra. Laboratory procedures did not yield significant amount of tephra (Figure A2.19).

KS-45C: Location—McPherson County, KS. Township and Range—SE ¼ Sec. 16, T. 18 S. R. 4 W.

KS-45C sample could not be located in the field.

KS-46: Location—McPherson County, KS. Township and Range—Center E ½ Sect. 28, T. 18 S., R. 5 W. GPS location—N 38.00° 27.00’ 30.20” and W 97.00° 52.00’ 20.20” (pit mine location) and N 38.00° 27.00’ 30.20” and W 97.00° 52.00’ 20.20” (field location).

Tephra was discovered in two different locations for this sample—one was in an abandoned pit-mine severely over grown with flora and the second location was approximately 200~300 meters NW of the pit mine in an active agriculture field. Tephra will be described for both the pit mine and field location, respectively.

Tephra is intermixed with silt and clay and not very pure, still visible through a hand lens are pumiceous shards. Tephra is a very pale-orange (10 Y/R 8/2) and there are no tephra outcrops found within the mine. Various digs within the mine yield impure tephra.

A very pinkish-gray (5 Y/R 8/1) tephra was discovered in a recently plowed field. The tephra did not form any competent beds on the surface. The field soil appeared to be white (N9) from a distance. Digging a 0.10 meter by 0.20 meter hole revealed a cleaner purer tephra sample. Thickness of this outcrop is undeterminable. It could be determined that the ash proceeded into the hill side (Figure A2.20 and Figure A2.21).

KS-47*: Location—Meade County, KS. Township and Range—NW ¼ SW ¼ Sec. 2, T. 31 S, R. 28 W. GPS location—N 37.00° 22.39 and W 100.00° 20.37.

Tephra is found in an abandoned quarry mine in Meade County. There are approximately 5.00 meters of Lava Creek B Tuff exposed in the walls of the quarry. Above the tephra is an approximate 2.00 meter intermixed zone of tephra, silt, and sand. Noted throughout the ash are various sedimentary structures (Figure A2.22).

KS-49*: Location—Meade County, KS Township and range—SE ¼ Sec. 23, T. 31 S., R. 28 W. GPS location—N 37.00° 22.39 and W 100.00° 20.37.

An approximate 1.50 meter of relatively pure Lava Creek B Tuff was located in several small prospect pits in Meade County. Noted in the ash has very distinct bedding (Figure A2.23 and Figure A2.24).

KS-50*: Location—Meade County, KS. Township and Range—NE ¼ SW ¼ SW ¼ Sec. 26, T. 32 S., R. 28 W. GPS location—N 37.00° 13.98 and W 100.00° 19.92.

Lava Creek B Tuff is 1. 50 meters thick and is located in an abandoned pit-mine. This deposit is located on private property and is not easily accessible (Figure A2.25).

KS-52: Location—Meade County, KS. Township and Range—NW ¼ NE ¼ Sec. 21, T. 33 S., R. 28 W. GPS location—N 37.00° 10.00' 07.30" and 100.00° 22.00' 10.20" and W 100.00° 22.00' 10.20".

An approximate 1.00 meter white (N9) relatively clean Huckleberry Ridge Tuff is exposed on top of greenish (56Y 8/1) mudstone along a large stream channel. At this location a sharp basal contact could be noted between the tephra and mudstone. The upper contact between the tephra and the overlying mudstone is gradational. Tephra is exposed on both sides of the channel. (Figure A2.26).

KS-54: Location—Nemaha County, KS. Township and Range—NW ¼ Sec. 31, T. 2 S. R. 13 E.

KS-54 sample could not be located in the field.

KS-56: Location—Ness County, KS. Township and Range—S ½ SW ¼ Sec. 6, T. 19 S., R. 26 W. GPS location—N 38.00° 25.00' 19.60" and W 100.00° 14.00' 25.30".

Tephra various between 0.50 to 1.00 meter thick and is located in an abandoned pit-mine. The tephra is white (N9) and no visible structures are noted, it appears to be massive. Noted in a conformable sequence is a 2.00 to 3.00 cm medium light-gray (N6) to medium-gray (N5) limestone. Due to the weathering of the ash this limestone bed is not competent and appears blocky (Figure A2.27).

KS-58: Location—Phillips County, KS. Township and Range—SW ¼ SW ¼ Sec. 14, T. 1 S., R. 18 W.

Sample was collected in a previous study by Van Fleet, 1999 and no outcrop description was provided (Figure A2.28).

KS-61*: Location—Pratt County, KS. Township and Range—S ½ SW ¼ Sec. 21, T. 27 S., R. 12 W. GPS location—N 37.00° 40.55 and W 98.00° 38.63.

An approximate 4.00 meter tephra was located in a large abandoned pit-mine. In this outcrop the purest tephra can be located in the basal section. Cross-bedding is preserved in the tephra and in the upper-tephra intermixing of ash and silt can be noted, this section also contains cross-beds (Figure A2.29).

KS-63A: Location—Rawlins County, KS. Township and Range—SE ¼ NW ¼ Sec. 14 T. 3 S., R. 35 W. GPS location—N 39.00° 47.00' 36.90" and W 101.00° 12.00' 55.90".

This outcrop is exposed in an old abandoned pit-mine and is 5.00 ~ 7.00 meters thick. Tephra is white (N9) to light-gray (N8) and is stained by the overlying silt. The siltstone is grayish-orange (10 YR 7/4). The tephra is relatively pure and clean and is located in the lower section of the mine. Cross-bedding is noted throughout the tephra (Figure A2.30).

KS-63B: Location—Rawlins County, KS. Township and Range—NW ¼ SW ¼ Sec. 22, T. 3 S. R. 35 W. GPS location—N 39.00° 46.00' 30.60" and W 101.00° 14.00' 26.80".

Tephra is found in an abandoned pit-mine. The tephra is white (N9) to light-gray (N9) and relatively pure and clean. Noted within the tephra were cross-beds and channels. The lower section of the outcrop is buried and true thickness cannot be determined, but exposed unit is approximately 0.50 meter. Above the tephra unit is an approximate 6.00 to 7.00 meter grayish-orange (10 YR 7/4) siltstone layer interbedded with conglomerate lenses (Figures A2.31, A2.32, A2.33, and A2.34).

KS-67:** Location—Reno County, KS. Township and Range—NE ¼ SW ¼ NW ¼ SE ¼ and SW 1//4 NE ¼ Sec. 14, T. 25 S., R. 8 W.

Sample was obtained from author's advisor. No outcrop description is available (Figure A2.35).

KS-70:** Location—Russell County, KS. Township and Range—NW ¼ NE ¼ and NE ¼ NW ¼ Sec. 2, T. 15 S., R. 11 W.

Sample was obtained from author's advisor. No outcrop or photo available.

KS-74: Location—Sheridan County, KS. Township and Range—NE ¼ SW ¼ Sec. 11 T. 8 S., R. 28 W. GPS location—N 39.00° 22.00' 17.60" and W 100.00 24.00' 54.20".

Tephra is not well exposed on the North slope of an abandoned pit-mine. Cleaner tephra was discovered by digging approximately 0.20 meters into the slope. Exposed tephra was light-gray (N8) and freshly exposed tephra was white (N9) (Figure A2.36 and Figure A2.37).

KS-76:** Location—Smith County, KS. Township and Range—NW ¼ NW ¼ Sec. 31, T. 3 S., R. 15 W.

Sample was obtained from author's advisor. No outcrop description available (Figure A2.38).

KS-78: Location—Trego County, KS. Township and Range—NW ¼ SE ¼ Sec. 28, T. 14 S., R. 21 W. GPS location—N 38.00° 48.00' 04.20" and W 99.00° 39.00' 28.70".

Tephra is white (N9) and is approximately 1.50 ~ 2.00 meters thick and is a relatively pure and clean outcrop. The outcrop was located on the side of huge cliff and immediately below the tephra is a massive grayish-orange (10 YR 7/4) siltstone bed (~1.00 meter) and above the tephra is approximately a 3.00 meter thick grayish-orange (10 YR 7/4) massive siltstone bed (Figure A2.39).

KS-79: Location—Trego County, KS. Township and Range—Center Sec. 36, T. 14 S., R. 21 W.

KS-79 sample could not be located in the field.

KS-81A: Location—Washington County, KS. Township and Range—NE Corner Sec. 25, T. 1 S. R. 4 E.

KS-81A sample could not be located in the field.

KS-81B: Location—Washington County, KS. Township and Range—NW Corner Sec. 30, T. 1 S., R. 4 W.

KS-81B sample could not be located in the field.

ADA 23: Location—Norton County, KS. Township and Range—NW ¼ NW ¼ Sec. 2, T. 4 S., R. 24 W. Sample was provided by the author's major advisor. No GPS markings. Field description is based on Swineford et al. 1955.

Approximately 3.00 meters of ash is located within silts and sandy-silts which overlies a thick fossiliferous-sand and gravel bed. Swineford et al. (1955) formally named this tephra the Dellvale Ash Bed. The Dellvale Ash is located in the middle Ash Hollow Member of the Ogallala Formation (Swineford et al., 1955). Based on stratigraphic position Swineford et al. (1955) believed this tephra unit to be Pliocene. However, current chemistry work suggests this outcrop is genetically similar to the Huckleberry Ridge Tuff of the Yellowstone Caldera making the Dellvale Ash Pleistocene and not Pliocene (Figure A2.40).

ADA 24: Location—Norton County, KS. Township and Range—SE ¼ SE ¼ Sec. 25, T. 3 S., R.25 W. Sample was provided by the author's major advisor. No GPS markings. Field description is based on Swineford et al. 1955.

Swineford et al. (1955) gave no field description for this outcrop location. They formally named this tephra the Calvert Ash Bed. The Calvert Ash is located in the lower Valentine Member of the Ogallala Formation (Swineford et al., 1955). Swineford et al. (1955)

believed this tephra to be Pliocene in age based on stratigraphic position. However, current chemistry work suggests the Calvert Ash at this location is genetically similar to the Huckleberry Ridge Tuff of the Yellowstone Caldera making the Calvert Ash Pleistocene and not Pliocene (Figure A2.41).

ADA 25: Location—Norton County, KS. Township and Range—SW ¼ SE ¼ Sec. 2, T. 3 S., R. 25 W. Sample was provided by the author's major advisor. No GPS markings are available for outcrop location. Field description is based on Swineford et al. 1955.

Tephra is approximately 2.00 meters thick and is exposed for approximately 0.40 km along a minor canyon. Swineford et al. (1955) formally named this tephra the Dellvale Ash Bed. The Dellvale Ash Bed is located in the middle Ash Hollow Member of the Ogallala Formation (Swineford et al., 1955). Swineford et al. (1955) believed this tephra to be Pliocene in age based on stratigraphic position. Current work proves inclusive on a source of eruption (Figure A2.42).

ADA 28: Location—Decatur County, KS. Township and Range—SE ¼ SW ¼ Sec. 8, T. 4 S., R. 9 W. Sample was provided by the author's major advisor. No GPS markings are available for outcrop location. Field description is based on Swineford et al. 1955.

No field description was provided for this outcrop of tephra. Swineford et al. (1955) formally named this tephra the Reamsville Ash Bed and describe it as being Pliocene based on stratigraphic position. The Reamsville Ash Bed is located in the middle Ash Hollow Member of the Ogallala Formation (Swineford et al., 1955). However, current chemistry work on the Reamsville Ash Bed suggests that it's closely related to the

Huckleberry Ridge Tuff of the Yellowstone Caldera and would therefore be Pleistocene and not Pliocene (Figure A2.43).

RD-NL: Location—Norton County, KS.

Sample provided by author's advisor. (Figure A2.44).

RD-CL: Location—Calvert County, KS.

Sample provided by author's advisor. (Figure A2.45).

RD-LA: Location—Alemena County, KS.

Sample provided by author's advisor. (Figure A2.46).

BTD-KS-01: Location—Ellsworth County, KS. Township and Range—SW ¼ Sec. 14, T. 16 S., R. 8 W. GPS location—N 38.00º 39.00' 10.20" and W 98.00º 10.00' 18.20".

Tephra is a very light-gray (N9) and is approximately 3.50 ~ 4.00 meters thick and approximately 95.00 meters long. The lower 1.50 meters is very contaminated with silt, and the upper section of the tephra contains small discontinuous lenticular beds of pure tephra ranging is size from 0.20 cm to 3 cm thick. The tephra is overlain by a moderate brown (5YR 4/4) to Dusky Brown (5 YR 2/2) silty to sandy beds approximately 0.50 ~ 1.00 meters thick (Figure A2.47).

BTD-KS-02: Location—Gove County, KS. Township and Range—NW ¼ SW ¼ Sec. 28, T. 15 S., R. 27 W. GPS location—N 38.00º 43.00' 23.40" and W 100º 20.00' 07.60"

Tephra is white (N8) and is approximately 5.00 meters thick and 60.00 meters long. The outcrop is massive with no sedimentary structures noted. It appears to be within an abandoned pit-mine that is highly overgrown with flora (Figure A2.48).

BTD-KS-03: Location—Sheridan County, KS. Township and Range—SW ¼ NW ¼ Sec. 11, T. 8 S., R. 28 W. GPS location—N 39.00º 19.00' 13.90" and W 100.00º 26.00' 29.70".

Tephra is White (N8) and is approximately 1.00~1.50 meters thick and is massive with no sedimentary structures found in the outcrop. The lower-half of the tephra is mixed with silt and the upper-half is relatively clean tephra. Immediately above the tephra unit is a very pale orange (10 YR 8/2) siltstone. Noted within the siltstone are igneous clasts ranging in size from 0.20 cm to 4 cm (Figure A2.49).

Pictures of tephra outcrops

Figure A2.1. Picture is of KS-1 tephra located in Chautauqua County, KS. Outcrop is small and blends into the surrounding terrain. Current work suggests KS-1 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera. Picture was taken by Van Fleet, 1999.

Figure A2.2. Picture is of KS-4 tephra located in Clark County, KS. Outcrop is approximately 1.50 meters thick and is located in a stream-cut. Current work suggests KS-4 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera. Picture was taken by Van Fleet, 1999.

Figure A2.3. Picture is of KS-11 tephra located in Ellis County, KS. Outcrop of tephra is approximately 1.00 meter thick. Current work suggests KS-11 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.4. Picture is of KS-15 tephra located in Gove County, KS. Outcrop is approximately 2.00~3.00 meters thick. Note sharp parallel-wavy contact between tephra and overlying silty-clay layer. Also noted in silty-clay layer were well-rounded igneous clasts ranging in size from 0.50 cm to 4.00 cm. Current work suggests KS-15 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.5. Picture is of KS-16 tephra located in Gove County, KS. Note how outcrop forms a 0.25-1.00 meter competent bed with a strike of N 50 E and a dip of 20°. Located in the background of photo is a second tephra outcrop approximately 15 meters above KS-16 denoted by red line. Current work suggests KS-16 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.6. Picture is of KS-16A tephra located in Gove County, KS. This outcrop is located approximately 15 meters above KS-16 and is approximately 0.25~0.50 meters thick. The two tephra units are separated by a silt layer that grades into a weathered conglomerate consisting of well-rounded to sub-angular igneous clasts ranging from 0.20 cm to 3.00 cm. Red line denotes base of KS-16A. KS-16 is not shown in picture. Current work suggests KS-16A is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

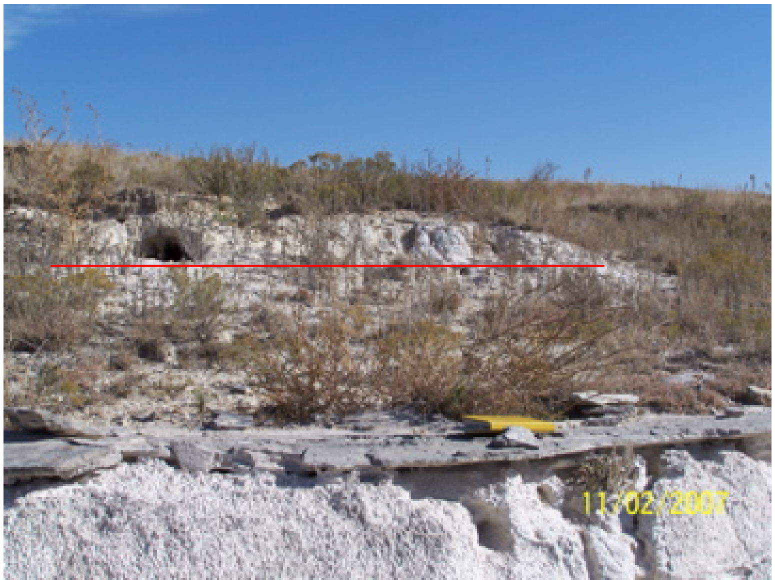

Figure A2.7. Picture is of KS-17 tephra located in Gove County, KS. Note possible 2.00cm~3.00cm algal limestone conformably overlying tephra sample and a second tephra sample named KS-17A located approximately 1.00 meter above algal limestone as denoted by red line. Current work suggests KS-17 and -17A are genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.8. Map view of a possible algal limestone that conformably overlies KS-17 tephra. Note the asymmetrical ripple marks on top of the limestone.

Figure A2.9. KS-19 tephra located in Gove County, KS. Tephra is approximately 1.00 meter thick. The tephra is located above the red line. Current work suggests KS-19 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.10. KS-20 tephra located in Gove County, KS. Tephra is approximately 0.50 meter ~ 1.00 meter thick. Tephra overlies a shale member of the Meade Formation. A 1.00 meter silt layer separates the tephra from the Meade Formation. Current work suggests KS-20 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.11. Outcrop of KS-23 in Grant County, KS. Tephra is approximately 5.00 meters thick. Current work suggests KS-23 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera. Picture was taken by Van Fleet, 1999.

Figure A2.12. Structure is composed of KS-26. This structure was located on the property of an abandoned pit-quarry where KS-26 was mined. Unable to locate the abandoned pit-mine due to overgrowth of flora. Current work suggests KS-26 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera. Picture was taken by Van Fleet, 1999.

Figure A2.13. KS-27 outcrop located in Jewell County, KS. Tephra is located in an abandoned pit-quarry that once mined KS-26. Current work suggests KS-27 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera. Photo taken by Van Fleet, 1999.

Figure A2.14. KS-31 outcrop located in Jewell County, KS. KS-31 was located along a fresh road cut in Jewell, County. The tephra is approximately 1.00 meter thick. Current work suggests KS-31 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera. Photo was taken by Van Fleet, 1999.

Figure A2.15. KS-37 located in Logan County, KS. Outcrop is approximately 0.50 meter thick. Current work suggests KS-37 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.16. KS-39 located in Logan County, KS. Outcrop is approximately 2.00 meter thick and 20.00 meters long. Current work suggests KS-39 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.17. KS-44 located in McPherson County, KS. This is a known Huckleberry Ridge Tuff (Izett and Wilcox, 1982). Outcrop is approximately 0.50 meters thick and is discontinuous and blocky.

Figure A2.18. KS-45A located in McPherson County, KS. Outcrop consisted of small gravel size impure-tephra clasts interbedded with silt. Could not isolate significant tephra during laboratory procedures.

Figure A2.19. KS-45B located in McPherson County, KS. Tephra sample is mixed with a significant amount of silt. Laboratory procedures yielded insignificant amount of tephra.

Figure A2.20. KS-46 located in McPherson County, KS. Tephra was located in an abandoned pit-mine that was overgrown with a significant amount of flora. Current work suggests KS-46 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.21. KS-46 located in McPherson County, KS. Outcrop of KS-46 was found approximately 200 ~ 300 meter NW of abandoned pit-mine adjacent to a field.

Figure A2.22. KS-47 located in Meade County, KS. Outcrop of KS-47 is a known Lava Creek B Tuff and is located in an abandoned pit-mine (Izett and Wilcox, 1982). Photo was taken by Van Fleet, 1999.

Figure A2.23. KS-49 located in Meade County, KS. Outcrop is a known Lava Creek B Tuff is located in several discontinuous outcrops. Photo provided by Van Fleet, 1999.

Figure A2.24. KS-49 located in Meade County, KS. Note the tephra has distinct parallel bedding. This sample is known as a Lava Creek B Tuff. Photo provided by Van Fleet, 1999.

Figure A2.25. KS-50 located in Meade County, KS. Tephra is approximately 1.50 meter thick and is located on private property. KS-50 is a known outcrop of Lava Creek B Tuff (Izett and Wilcox, 1982). Photo provided by Van Fleet, 1999.

Figure A2.26. KS-52 located in Meade County, KS. Tephra is approximately 1.25 meter thick and is located Hwy 23 about 4 miles south of Meade City. KS-52 is a known outcrop of Huckleberry Ridge Tuff (Izett and Wilcox, 1982). Red line is approximately 1 meter.

Figure A2.27. KS-56 located in Ness County, KS. Tephra is approximately 1.50 meters thick and was found in an abandoned pit-mine. Current work suggests KS-56 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.28. KS-58 located in Phillips County, KS. Current work cannot suggest a source of eruption for KS-58. Photo provided by Van Fleet, 1999.

Figure A2.29. KS-61 located in Pratt County, KS. Upper tephra unit is a silty-ash mixture the purest ash is located in the basal section. Also noted in the outcrop were cross-beds. Current work suggests KS-61 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera. Photo provided by Van Fleet, 1999.

Figure A2.30. KS-63A located in Rawlins County, KS. Tephra is located in an abandoned pit-mine. Current work suggests KS-63A is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.31. KS-63B located in Rawlins County, KS. Found interbedded with tephra were conglomerate lenses. Current work suggests KS-63B is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.32. KS-63B located in Rawlins County, KS in an abandoned pit-mine.

Figure A2.33. KS-63B located in Rawlins County, KS. Note scoured channel that cut down into the tephra.

Figure A2.34. KS-63B located in Rawlins County, KS. Note cross-beds within very pure tephra unit.

Figure A2.35. KS-67 is located in Reno County, KS. Current work suggests KS-67 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera. Photo was taken by Van Fleet, 1999.

Figure A2.36. Location of KS-74 is in Sheridan County, KS. Tephra is exposed on a North facing slope of an abandoned pit-mine. Current work suggests KS-74 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.37. Location of KS-74 is in Sheridan County, KS. Cleaner tephra was discovered after digging approximately 0.20 meters.

Figure A2.38. KS-76 located in Smith County, KS. Current work cannot suggest a source of eruption for KS-76. Photo provided by Totten, M.W., unpublished work.

Figure A2.39. Location of KS-78 is in Trego County, KS. The tephra is located on a cliff face. Current chemical work on KS-78 suggests it is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.40. ADA-23 located in Norton County, KS. Tephra unit is described as being Pliocene by Swineford, et al. 1955. Current work suggests the ADA-23 is genetically similar to Huckleberry Ridge Tuff. The ADA-23 would be a Huckleberry Ridge Tuff and Pleistocene and not Pliocene. Photo provided by Totten, M.W., unpublished work.

Figure A2.41. ADA-24 located in Norton County, KS on the Calvert Mine Property. Tephra unit is described as Pliocene by Swineford, et al. 1955. Current work suggests the ADA-24 is genetically similar to Huckleberry Ridge Tuff. The ADA-24 would be a Huckleberry Ridge Tuff and Pleistocene and not Pliocene. Photo provided by Totten, M.W., unpublished work.

Figure A2.42. ADA-25 located in Norton County, KS. Tephra unit is described as Pliocene by Swineford, et al. 1955. Current work proves inclusive in determining a source of eruption for the ADA-25. Photo provided by Totten, M.W., unpublished work.

Figure A2.43. ADA-28 located in Decatur County, KS. Tephra unit is described as Pliocene by Swineford, et al. 1955. Current work suggests the ADA-28 is genetically similar to the Huckleberry Ridge Tuff and therefore would be Pleistocene and not Pliocene. Photo provided by Totten, M.W., unpublished work.

Figure A2.44. RD-NL is a sample collected from Van Fleet, 1999 and is located in Norton County, Kansas. Current work cannot find an eruption source. Photo provided by Totten, M.W., unpublished work.

Figure A2.45. RD-CL is a sample collected from Van Fleet, 1999 and is located in Calvert County, Kansas. Current work suggests the sample is genetically related to the Huckleberry Ridge Tuff. Photo provided by Totten, M.W., unpublished work.

Figure A2.46. RD-LA is a sample collected from Van Fleet, 1999 and is located in Norton County, Kansas. Current work cannot suggest a source of eruption for this sample. Photo provided by Totten, M.W., unpublished work.

Figure A2.47. BTD-KS-01 is located in Ellsworth County, KS. Tephra is found along a road and is previously not described in any published literature. Tephra unit was to contaminated thus laboratory procedures yielded insignificant amount of tephra to be analyzed.

Figure A2.48. BTD-KS-02 is located in Gove County, KS. Tephra is found on the private property of Mr. Rodrick Bentley and does not appear in any published literature. Tephra appears to be in an abandoned pit-mine, however, it was overgrown with heavy flora. Current work suggests BTD-KS-02 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.

Figure A2.49. BTD-KS-03 is located in Sheridan County, KS. Tephra outcrop was found along Highway 23 and does not appear to be in any published literature. Current work suggests that BTD-KS-03 is genetically similar to Lava Creek B Tuff of the Yellowstone Caldera.