VOLCANIC LITHOFACIES AND GEOCHEMISTRY OF CAMBRIAN RIFT-
RELATED RHYOLITES IN THE WEST TIMBERED HILLS, ARBUCKLE
MOUNTAINS, SOUTHERN OKLAHOMA

by

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CHAPTER 1: INTRODUCTION

**General Setting and Research Goals:**

The Carlton Rhyolite of southern Oklahoma is the uppermost unit in the bimodal Neoproterozoic to Cambrian Wichita Igneous Province of the Southern Oklahoma Aulacogen (SOA). The SOA is a northwest-southeast-trending rift that formed in the Neoproterozoic(?) to Cambrian as a failed rift arm or leaky transform fault during the opening of the Iapetus Ocean along the southern margin of Laurentia. TCU workers have studied the rhyolites in the Wichita Mountains of southwest Oklahoma and the East Timbered Hills (ETH) in the Arbuckle Mountains farther east. The area of interest for this project is the West Timbered Hills (WTH), where fairly extensive rhyolite outcrops occur. The area was previously described by Uhl (1932), who only mapped the overall boundaries of the rhyolite. Past work in the ETH (Eschberger, 2012; Eschberger et al., 2014) has shown the area to be proximal to rhyolitic source vent(s). My project is the first modern study of the rhyolites in the West Timbered Hills.

The questions to be addressed are: 1) What volcanic lithofacies are present in the WTH?, 2) Does the area offer evidence for laterally extensive flows (flood rhyolites) of the same type found in some other intraplate igneous provinces?, 3) Were the rhyolites derived from source reservoirs geochemically distinct from A-type rhyolites in other parts of the SOA? An additional outcome of this project is a detailed map of all the Cambrian igneous rocks in the WTH, which will be submitted to the Oklahoma Geological Survey for publication. This mapping was carried out in collaboration with TCU graduate student Chelsea Toews, who studied felsic and mafic hy-
pabyssal intrusions and polymict igneous breccia outcrops and associated damage zones in the same area. Preliminary results of this research have been presented by Boro et al. (2015).

**Research Methods and Analytical Techniques**

**Field Mapping**

The extent of rhyolite outcrops in the WTH spans ~10 km² and was mapped at a scale of 1:6000 on a topographic orthophoto overlay which was made using 2-m DEM data in ArcGIS (Plate I). The entire area was mapped in detail on foot, and GPS coordinates were taken when precise location on the map was otherwise uncertain. The unconformable contact between the overlying Reagan Sandstone and the Carlton Rhyolite (and other associated igneous units) was also mapped using previous work published by the Oklahoma Geological Survey (Johnson, 1990) as a guide. Measurements were taken of attitudes of flow banding, flow lineations, flow folds, and columnar jointing in the rhyolites and of bedding in tuffaceous mudstone intercalated with the rhyolites. A few bedding attitudes were also measured in the Reagan Sandstone.

Physical volcanological features such as spherulites and lithophysae were documented and labeled on the map. Generalized cross sections of individual flows were constructed. Zones of closely spaced tectonic joints that occur with cataclasite or fault breccia in some cases were also mapped.

**Petrographic Analyses**

Fifty-nine thin sections of rhyolite and volcaniclastic interbeds were prepared by Spectrum Petrographics in Vancouver, WA from pre-cut chips made in the TCU rock preparation laborato-
ry. Numerous photomicrographs were taken in plane and polarized light of important features and representative examples are included in this thesis. Thin sections were examined in detail, paying particular attention to features present which would help to determine emplacement mechanisms and devitrification and alteration overprints.

Maximum phenocryst sizes in individual flows were measured, and phenocryst contents were estimated visually using cut slabs and thin sections. Detailed point counting was not attempted because alteration in many cases made it difficult to distinguish phenocrysts from groundmass features and alteration products.

**Geochemical Analyses**

Twelve bulk-rock (~8 kg) samples of rhyolite flows were collected for geochemical analysis. Samples were washed thoroughly with soap and water to remove any contaminants and then were broken into smaller pieces with a crack hammer in the field or the rock preparation laboratory until they could fit into a large steel jaw crusher to form smaller chips. To minimize contamination for each sample, the crusher was pre-contaminated by crushing a small part of the sample, which was then discarded. The crusher was then thoroughly cleaned again before crushing the main part of the sample. These small chips were hand picked to remove those showing alteration. The remaining chips were then run through a small ceramic jaw crusher.

The crushed chips for each sample were homogenized and split using the cone-and-quarter technique. Sample splits weighing 80-120 g were sent to the GeoAnalytical Laboratory at Washington State University for chemical analysis. There, 28 g of chips were selected for pulverization using a tungsten carbide swing mill, and 3.5 g of this powder was pressed and melted into
glass beads for analysis. Further information on sample preparation, analytical techniques, and precision and accuracy can be found at: http://environment.wsu.edu/facilities/geolab/technotes/.

All samples were analyzed for major elements and some trace elements (Ni, Cr, V, Ga, Cu, Zn) using x-ray fluorescence (XRF), and loss on ignition (LOI) values were also obtained. More precise trace-element analyses (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ba, Th, Nb, Y, Hf, Ta, U, Pb, Rb, Cs, Sr, Sc, Zr) were done by inductively coupled plasma-mass spectrometry (ICP-MS). Additional information for these analytical procedures, precision, and accuracy can be found in the aforementioned URL.
CHAPTER 2: REGIONAL GEOLOGIC SETTING

Overview

The history of emplacement and present-day exposure of Cambrian igneous rocks in the Wichita Igneous Province of southern Oklahoma involves both intraplate and active compressional or transpressional tectonic settings. These rocks were formed ~530 Ma during rifting along the southern margin of Laurentia and the opening of the southern Iapetus Ocean, which is related to the breakup of the Rodinia supercontinent. The igneous rocks were deposited during the formation of a rift striking into the Laurentian interior in southern Oklahoma (Fig. 1), and is one of a series of rifts that developed during this breakup event. The rift is >100 km wide as indicated by gravity and magnetic anomalies (Keller and Stephenson, 2007). There are two competing theories on how the rift in southern Oklahoma may have formed. The first one is that the rift is a failed third arm that developed at a high angle to the main rifts that formed along the southern margin of Laurentia and underwent seafloor spreading. This theory was first proposed by Hoffman et al. (1974) and is supported by a distinctive three-pronged gravity anomaly on the Oklahoma-Texas border pointed out by Keller and Stephenson (2007). The second theory, proposed by Thomas (1991, 2011), is that the rift developed in association with a leaky transform fault. This transform fault is inferred by Thomas (1991, 2011) to define the west-northwest-trending ancient continental margin that runs between Alabama and Oklahoma. Either theory may require an anomalous heat source to explain the magmatism in the rift. This topic is outside the scope of my thesis, but either tectonic setting could produce the bimodal igneous province present in southern Oklahoma.
Fig. 1. Carlton Rhyolite Group with estimated volume (see text for discussion). East and West Timbered Hills are shown (ETH and WTH). Modified from Hanson et al. (2013). Early Paleozoic continental margin from Keller and Stephenson (2007).
The Southern Oklahoma rift zone is classically recognized as an aulacogen (Shatski, 1946, cited by Hoffman et al., 1974) and generally is referred to as the Southern Oklahoma Aulacogen (SOA). A large subsurface basin, located to the south of the SOA, contains Proterozoic strata, which may indicate a pre-existing line of structural weakness along which the Cambrian rift developed (Pratt et al., 1992). Mesoproterozoic felsic rocks, ~1.4 Ga in age, occur in the subsurface on both the north and south sides of the rift and are locally exposed north of the rift margin in the eastern Arbuckle Mountains (Ham et al., 1964; Rohs and Van Schmus, 2007). Further evidence that this rift follows a pre-existing line of weakness is a suite of northwest-trending microgranite and diabase dikes in the eastern Arbuckle Mountains that intrude the 1.4 Ga felsic rocks and are considered to be around the same age as those rocks (Denison, 1982, 1995). This seems to indicate an underlying structural weakness in that direction in the region and may be why the third failed rift arm or leaky transform developed where it did.

Following the igneous activity, a eustatic sea level rise led to burial of the igneous rocks by sediments up to 5 km thick over a span of time from the Late Cambrian into the Mississippian. Intense deformation of these rocks subsequently occurred in the Pennsylvanian and Early Permian (Ham, 1973; Perry, 1989) during the formation of the supercontinent Pangaea. During this tectonism the SOA was partially inverted by the reactivation of major Cambrian rift-related-normal faults as reverse faults in a compressional to transpressional regime (McConnell, 1989; Perry, 1989). Fault blocks were thrust to the northeast and provided the developing Anadarko basin with sediment (Gilbert, 1983; Johnson et al., 1988). This deformation is thought to be the result of either collisional Ouachita orogenesis along the southeastern margin of the continent, or
far-field stresses transmitted inward from the Cordilleran margin to the west (Perry, 1989; Ye et al., 1996).

**Wichita Igneous Province**

Ham et al. (1964) provided the first synthesis of the rift-related igneous rocks within the SOA using both surface and subsurface data and established a formal nomenclature for these rocks, which was modified by Powell et al. (1980). Many of the geologic interpretations that Ham et al. (1964) made have been confirmed or at least not refuted even after 50 years of research and changes in geologic thinking.

Basement wells that postdate the work of Ham et al. (1964) provide new subsurface data on igneous relations (Puckett, 2011; Puckett et al., 2014) and some of the new results from these wells are discussed below. Most importantly it was found that in the subsurface, the Carlton Rhyolite is intercalated with extrusive basalt and in all of the well cuttings examined so far, there is no evidence of caldera-type rhyolitic volcanism such as widespread ignimbrite deposits (Puckett et al., 2014). Some rhyolite flows in the subsurface have thicknesses > 400 m and show similar vertical zonations as described in outcrop by Hanson et al. (2014) and discussed below.

Exposures of the Cambrian Wichita Igneous Province are relatively limited and are present in the Wichita Mountains in southwest Oklahoma and in the Arbuckle Mountains farther east. The province is strongly bimodal and includes the Raggedy Mountain Gabbro, Navajoe Mountain Basalt-Spilite, Carlton Rhyolite, and Wichita Granite Groups (Fig. 2) (Ham et al., 1964; Powell et al., 1980).
Fig. 2. Schematic cross section of igneous rocks exposed in the Wichita Mountains, modified from Hogan and Gilbert (1998) and Hanson et al. (2013). The Glen Mountains Layered Complex and Roosevelt Gabbros make up the Raggedy Mountain Gabbro Group. The Navajo Mountain Basalt-Spilite Group is not included as it only occurs in the subsurface.
The term Raggedy Mountain Gabbro Group was introduced by Ham et al. (1964) to describe all gabbroic rocks in the Wichita Igneous Province. This group was later subdivided into two separate units, the Glen Mountains Layered Complex (GMLC) and Roosevelt Gabbros, by Powell et al. (1980), and these terms are now used more commonly in the literature when discussing these rocks. The GMLC is the oldest exposed unit in the province and is interpreted to represent the beginning of extension in the region (Gilbert, 1983).

The GMLC is an anorthosite-rich, layered mafic intrusion which shows multiple cyclic layers. Detailed field mapping and subsurface data indicate the presence of three distinct layered units within the GMLC: anorthosite, anorthositic gabbro, and troctolite and olivine gabbro, which each show rhythmic and cryptic layering (Powell, 1986; Cooper, 1991). The GMLC is intruded by the Roosevelt Gabbros. After emplacement, the GMLC was tilted slightly to the north and upper parts of the complex (~2-4 km) were removed by erosion (Powell and Phelps, 1977). McConnell and Gilbert (1990) attribute this slight dip to the north to normal-fault block rotation during development of the rift complex.

The Roosevelt Gabbros are composed of a series of relatively small, partly layered plutons which intrude the Glen Mountains Layered Complex in several different areas. They are distinguished from the latter unit by their relatively high biotite content (Powell, 1986). These rocks are generally hydrous, olivine-bearing rocks which occur as relatively large cylindrical or sill-like bodies, or thin (<4 m), dike-like intrusions (Cooper, 1991). No outcrops belonging to either the Glen Mountains Layered Complex or the Roosevelt Gabbros have been found in the Arbuckles.
The Navajoe Mountain Basalt-Spilite Group (NMBSG) is only present in the subsurface in the western part of the Wichita Igneous Province and has basaltic, spilitic, and andesitic compositions. Wells penetrate thicknesses of ~250-320 m in a belt along the southern flank of the Wichita Mountains, although none have reached the base of the group (Ham et al., 1964). Gilbert (1983) believes these rocks represent the extrusive equivalent of the Glen Mountains Layered Complex. This has yet to be proven because of the lack of isotopic age data for the basalts. Ham et al. (1964) believed that the NMBSG is unconformably overlain by the Carlton Rhyolite. If this is the case, the new basalts discovered by Puckett et al. (2011, 2014) need to be distinguished from the NMBSG.

Brueseke et al. (2014) and Hobbs et al. (2015) provide geochemical evidence from basalt samples collected from three different wells documented by Puckett et al. (2014). Geochemical results indicate that the basaltic magmas originated from ocean-island-basalt (OIB) sources and evolved by fractional crystallization of typical mafic mineral assemblages. Also Brueseke et al. (2014) point out that basalt volcanism was common throughout the aulacogen, which supports the hypothesis that the SOA rift formed as a failed third rift arm and is inconsistent with small-volume alkalic volcanism which would be expected if the igneous province formed as a result of a leaky transform fault as proposed by Thomas (1991, 2011).

The Glen Mountains Layered Complex has provided a Sm-Nd internal isochron age of $528 \pm 29$ Ma (Lambert et al., 1988). One of the Roosevelt Gabbros that penetrates the Glen Mountains Layered Complex yielded $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende and biotite dates of $533 \pm 2$ and $533 \pm 4$ Ma, respectively (Hames et al., 1998). The same body of Roosevelt gabbro has yielded a U-
Pb zircon age of 552 ± 7 Ma (Bowring and Hoppe, 1982) and a U-Pb titanite age of 577 ± 2 Ma (Hogan and Amato, 2015). Additional work is needed to resolve these age discrepancies.

As rifting entered later stages, the igneous activity became dominated by voluminous rhyolites and granites, represented by the Carlton Rhyolite and Wichita Granite Groups (Ham et al., 1964). The Carlton Rhyolite Group was extruded on to the erosional surface developed on the Glen Mountains Layered Complex. The Carlton Rhyolite has yielded U-Pb zircon ages of ~539-530 Ma (Wright et al., 1996; Hanson et al., 2009; Thomas et al., 2012; Hogan and Amato, 2015). Sheet granites from the Wichita Granite Group intrude the base of the Carlton Rhyolite (Fig. 2) and are thought to be comagmatic with it (Ham et al., 1964; Gilbert, 1982; Hogan and Gilbert, 1997). Diabase dikes crosscut all other igneous units in the region (Taylor, 1915; Denison, 1995). The dikes are best developed in the Mesoproterozoic basement exposed in the eastern Arbuckle Mountains. They run mostly parallel to the northwest direction of structural weakness that seems to exist in this region, which the rift followed and which is represented by the earlier suite of dikes in this area that was mentioned previously. The majority of the dikes in the eastern Arbuckles are thought to be Cambrian in age due to increasing abundance proximal to the rift zone (Denison, 1995; Lidiak et al., 2014). However, most of these Cambrian dikes are thought to be pre-rhyolite, as the number of dikes cutting the rhyolite exposures in the Arbuckle Mountains is significantly less than the number cutting older basement rocks.

The Carlton Rhyolite Group is the most extensive basement rock exposed at the surface and is the uppermost main igneous unit within the SOA. The rhyolites extend for ~40,000 km² in the subsurface, as indicated by geophysical and drilling evidence (Ham et al., 1964; Hanson et al., 2013). The greatest known exposed thickness of Carlton Rhyolite occurs at Bally Mountain.
in the Wichita Mountains, where a series of rhyolite flows forms a succession ≥2 km thick (Hanson et al., 2013, 2014). This is a minimum thickness because the base of the succession is truncated by a Pennsylvanian fault. The greatest thickness penetrated by drilling is 1.4 km in the Arbuckle Mountains region (Ham et al., 1964). Though the northern extent is uncertain due to deep burial, this volcanic field compares in areal extent and volume with the Miocene to Holocene Snake River Plain/Yellowstone magmatic system (Hanson et al., 2011).

The main outcrops of the Carlton Rhyolite occur in the Wichita Mountains (Fig. 1). Extensive work has been done on these outcrops by TCU workers (Bigger and Hanson, 1992; Philips, 2002; Burkholder, 2005; Finegan and Hanson, 2014; Hanson et al., 2014), and at least 31 flows have been documented there (Finegan and Hanson, 2014; Hanson et al., 2014). Figure 3 shows a schematic cross section of an idealized Carlton Rhyolite flow in the Wichita Mountains from Hanson et al. (2014). Not all flows show the complete sequence of zones. However, the zones tend to occur in the same vertical sequence wherever they are present. Many flows are separated by thin layers of tuffaceous mudstone, typically ~1 m thick, and a few flows are intercalated with thick sequences (up to 100 m) of bedded volcaniclastic rocks.

The Carlton Rhyolite is only exposed in the Wichita and Arbuckle Mountains (Fig. 1). The rhyolite in the western Arbuckle Mountains was formally known as the “Colbert Rhyolite” or “Colbert Porphyry” (Ham, 1973), named after exposures along Colbert Creek in the WTH, but this unit is continuous in the subsurface with rhyolite outcrops in the Wichita Mountains. All of these felsic volcanic rocks will therefore be referred to as Carlton Rhyolite in this thesis.

Stratigraphic relations in the Arbuckle Mountains indicate that in some areas the rhyolites ponded against a major rift fault that existed along the northern margin of the rift zone at that
Fig. 3. Schematic generalized cross section for idealized zonation of rhyolite flows in the Wichita Mountains. From Hanson et al. (2014).
time (Ham et al., 1964). Ham et al. (1964) believed that Precambrian basement was initially uplifted to form a pre-rhyolite fault scarp with at least 1.4 km of throw. This fault was then reactivated during late Paleozoic deformation, when the Arbuckle Anticline was thrust over the Mesoproterozoic Arbuckle crystalline rocks (Ham et al., 1964). However, geophysical evidence suggests the rhyolites poured across the rift-bounding faults and extended farther north (Keller and Stephenson, 2007). The rhyolites in the SOA are thought to have erupted effusively from fissure-type vents, as there is no evidence for the presence of calderas (Hogan and Gilbert, 1998; Puckett et al., 2014).

Granite sheets within the Wichita Mountains form extensive (at least 55 km long), thin (~0.5 km thick), subhorizontal intrusions (Powell et al, 1980; Myers et al. 1981). Both fine- and coarse-grained lithodemic units occur within the Wichita Granite Group in the Wichita Mountains (Hogan et al., 2000). Hogan et al. (2000) recognized a distinct style of intrusive relationship between the different granites and the associated rhyolites. This style is described as a cycle which begins with eruption of voluminous rhyolites, which are then intruded by fine-grained sheet granites, which are subsequently intruded by coarser granites. The fine-grained granite sheets, which are abundant throughout the Wichita Mountains, include the Mount Scott granite sheet located in the eastern and central Wichita Mountains (Price, 2014). The coarse-grained granites are less abundant than the fine-grained and include the Quanah granite sheet of the eastern Wichita Mountains.

Previous geochemical studies show the Carlton Rhyolite, associated felsic hypabyssal intrusions, and Wichita granites plot within the A-type field on the discrimination diagram developed by Whalen et al. (1987) (Hanson and Eschberger, 2014). The term ‘A-type’ is given to fel-
sic igneous rocks which are generally rich in fluorine, anhydrous (H₂O < 1%), have high FeO*/MgO ratios, high K₂O/Na₂O ratios, higher than average temperatures for felsic magmas (900-1050 °C), and show enrichment in high-field-strength elements (Bonnichsen and Kaufman, 1987; Whalen et al., 1987; Eby, 1990). A-type felsic rocks are normally found in anorogenic tectonic settings such as rift zones or continental hot-spots (Whalen et al., 1987; Eby, 1990).

Zr and P₂O₅ geothermometry indicates magmatic temperatures for the Carlton Rhyolite and Wichita granites of ~900-950 °C (Hogan and Gilbert, 1997; Price et al. 1999). Price et al. (1999) point out that the presence of coexisting magmatic titanite and fluorite in the Wichita granites is indicative of elevated fluorine contents based on mineral equilibria relations. This is consistent with high F in biotite and amphibole (Hogan and Gilbert, 1995; Hogan et al., 2000).

A-type felsic provinces are known for producing laterally extensive rhyolite flows, sometimes called flood rhyolites (Henry et al., 1990; McPhie et al., 2008). To produce such a different style of felsic flow, viscosity must be lowered. Dingwell et al. (1985) found that, for silicic melt compositions with SiO₂ ~ 75 wt. % and Na/Al ratios of 1 at 1000°C, the viscosity of a melt can be lowered by one order of magnitude per each weight percent of F added to the melt. As mentioned earlier, A-type rocks are known for having elevated F levels. This may be, at least in part, the mechanism by which they acquire relatively low viscosities.

It is important to note that some rhyolites and granites in the SOA are clearly peralkaline, geochemically and in hand sample as indicated by the presence of aegirine and arfvedsonite (Myers et al., 1981; Hanson and Eschberger, 2014). By definition, peralkaline rocks have Na₂O + K₂O / Al₂O₃ > 1 in molecular proportions, but this geochemical signature is easily disturbed due to alkali mobility during alteration (e.g., Tollo et al., 2004). This has probably happened in the Carl-
ton Rhyolite, because some of the rhyolite units plot within the peralkaline field on the Winchester and Floyd (1977) TiO₂/Zr vs Nb/Y discrimination diagram, although these units do not show a peralkaline signature in terms of their major oxide contents (Hanson and Eschberger, 2014).
CHAPTER 3: GEOLOGIC SETTING OF THE STUDY AREA

The study area is located in the Arbuckle Mountains in the western part of the Arbuckle Anticline (Fig. 4). There are two areas in which the core of the anticline is exposed, the ETH and the WTH (Figs. 4 and 5), where both the rhyolites and overlying sedimentary units are deformed by a complex series of faults. The Washita Valley Fault Zone (WVFZ), which is the principal through-going fault of the Arbuckle Mountains, runs just north of the Timbered Hills area and strikes ~N60° W (Fig. 4), which is the general trend of most structures in southern Oklahoma (Ham et al., 1964). The eastern part of the fault separates the Arbuckle Anticline from the Tishomingo Anticline, which exposes Precambrian granites and gneisses. The plane of the WVFZ has a complicated geometry. In the Timbered Hills area, the fault dips southwest with northeast transport but farther east the nature of the fault changes and it dips steeply to the northeast and has southwest transport (Denison, 1995).

Ham (1973) used Pennsylvanian conglomerates and sandstones derived from erosion of older units in the Arbuckles to put timing constraints on folding and uplift in the region. He showed that the Arbuckle Anticline was one of the main structures to form in the region and developed in the latest Pennsylvanian to earliest Permian. The formation of the Arbuckle Anticline and final inversion of the rift were pre-dated by slow but continuous uplift of the nearby Hutton and Tishomingo Anticlines (Fig. 4) (Ham, 1973) and occurred during deposition of the uppermost Pennsylvanian Collings Ranch and Vanoss Conglomerates, each forming an angular unconformity with underlying units.

Cambrian igneous rocks in both the WTH and ETH are overlain disconformably by the Upper Cambrian Timbered Hills Group, consisting of the Reagan Sandstone and the
Fig. 4. Geologic map of the Arbuckle Mountains, from Ham (1973), modified by Eschberger (2012). WTH: West Timbered Hills; ETH: East Timbered Hills; WVFZ: Washita Valley Fault Zone; RF: Reagan Fault; SF: Sulphur Fault. The WVFZ separates the western Arbuckle Mountains (including the Arbuckle Anticline) from the eastern Arbuckle Mountains (including the Tishomingo, Belton, and Hunton Anticlines.)
Fig. 5. Geologic map of the western Arbuckle Mountains. See next page for legend. Modified from Johnson (1990) and Eschberger (2012). WTH = West Timbered Hills, ETH = East Timbered Hills, WRF = Washburn Ranch Fault.
Honey Creek Formation. The northeastern extent of the main occurrence of Cambrian igneous rocks is generally delimited by the WVFZ (Johnson, 1990), which is the northeastern boundary of my field area.

Mapping of the rhyolite in the East Timbered Hills by Eschberger (2012) and Eschberger et al. (2014) revealed two rhyolite flows separated by a 60-m-thick sequence of interbedded volcaniclastic mudstones, sandstones, and conglomerates. The upper rhyolite flow is at least 600 m thick. The lower rhyolite flow is >300 m thick but the true thickness is unknown due to faulting. Eschberger (2012) and Eschberger et al. (2014) also mapped four different types of hypabyssal felsic intrusions cutting the rhyolites.

In addition to the rhyolites present in the WTH, Uhl (1932) described a polymict igneous breccia that is associated with diabase in one part of that area. The breccia was examined to some extent by Eschberger (2012) and Eschberger and Hanson (2014), and more detailed work on it and associated diabase and microgranite intrusions can be found in Toews (2015).
CHAPTER 4: CARLTON RHYOLITE GROUP IN THE WEST TIMBERED HILLS

Overview

The WTH are located in the northwest corner of Murray County, just south of Highway 7 (easily accessed by Interstate 35) and the Murray-Garvin County line. Interbedded volcaniclastic rocks within the rhyolite succession generally dip ≤7-18° to the east. A general sense of the southern and western extents of the outcrop area can be gathered from interstate overlooks by viewing the newly installed wind farm in the area because the turbines are built on the rocks exposed there. It is hard to get a sense of the overall structure in this region because of the pervasive faulting which affects the rocks. Easiest access to the field area is by roads which lead from the Cross-Bar RV and ATV Park run by the city of Davis. The ATV park has trails which cover the eastern part of the rhyolite outcrops. The majority of the outcrops farther west are on private ranch land owned by Mike Warren, Garry Weiss, and Royce Jones. Part of the field area is leased and quarried by Hanson Aggregates LLC.

The best exposures of rhyolite are on the ATV park and Royce Jone’s ranch, which have deep valleys and ATV paths clear of vegetation, making outcrops easier to see. Much of the outcrop throughout the WTH occurs in a series of deep, and in some cases, wide valleys which expose steep walls cut into the igneous rocks. The valleys generally trend north-south and can be filled with rather swift-moving water after heavy rains, but are usually occupied by trickling streams easy to forge. The maximum relief is ~100 m and elevation in the field area ranges from 325 m to 430 m above sea level. The area is heavily vegetated, which along with the tick and rattlesnake population, make studying these rocks in the winter months a priority. The boundaries
of the rhyolite outcrops are generally delimited by contact with the overlying Reagan Sandstone; however the Washburn Ranch Fault (Figs. 5 and 6), which trends roughly west-northwest, juxtaposes rhyolite against Upper Cambrian to Lower Ordovician limestones and dolomites.

**Rhyolites and associated volcaniclastic rocks in the West Timbered Hills**

Seven different rhyolite flows, labeled Flows 1-7 from east to west, have been mapped in the WTH and span an area of ~10 km². Plate I shows the mapped extent of these units, and a smaller version of that map is included in the text as Figure 6. Exposed parts of the flows range in thickness from ~20-80 m, but only in one area is the total thickness of a flow exposed. Two different volcaniclastic interbeds have been found and consist of bedded, dominantly rhyolitic volcaniclastic rocks ranging in thickness from ~15-20 m, with local zones of peperite developed at the bases of the overlying rhyolite flows (discussed later). Diabase and microgranite intrusions and masses of discordant polymict igneous breccia, interpreted to be conduits for basaltic phreatomagmatic volcanoes, commonly crosscut the flows (Toews, 2015).

During the course of mapping, I was able to distinguish individual flows from each other based on phenocryst contents. This and other relevant flow information can be found in Table 1. Phenocryst phases present include plagioclase, K-feldspar, both partly replaced by sericite, and mafic crystals now replaced by green clays. K-feldspar phenocrysts are now orthoclase, but were presumably either sanidine or anorthoclase at the time of emplacement. Total phenocryst contents range from <2% up to 20%. No quartz phenocrysts were found in any of the flows.

Most WTH rhyolite flows show similar vertical zonations to those discussed by Hanson et al. (2014) and summarized in Chapter 2. Each flow that follows the model exhibits, at least in
Fig. 6. Generalized geologic map of the West Timbered Hills with units from Carlton Rhyolite Group labeled. Geology outside area of igneous rocks taken from Johnson (1990). For more detailed map key, see Plate I.
<table>
<thead>
<tr>
<th>Phenocryst Content</th>
<th>Flow 1</th>
<th>Flow 2</th>
<th>Flow 3</th>
<th>Flow 4</th>
<th>Flow 5</th>
<th>Flow 6</th>
<th>Flow 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenocrysts Present</td>
<td>K-feldspar, plagioclase, some mafic crystals replaced with green clays</td>
<td>K-feldspar, plagioclase, mafic crystals (including fayalite) replaced with green clays</td>
<td>K-feldspar, some mafic crystals replaced with green clays</td>
<td>K-feldspar and plagioclase</td>
<td>K-feldspar, plagioclase, some mafic crystals replaced with green clays</td>
<td>K-feldspar and sparse mafic crystals replaced with green clays</td>
<td>K-feldspar, plagioclase, some mafic crystals replaced with green clays</td>
</tr>
<tr>
<td>Maximum Phenocryst Size and Shape</td>
<td>≤7 mm, subequant</td>
<td>12 mm, some ovoid, tabular K-feldspar</td>
<td>20 mm, K-feldspar exhibits elongate tabular habit</td>
<td>&lt;1 mm, obscured by alteration in hand sample</td>
<td>10 mm, K-feldspar is ovoid and tabular</td>
<td>15 mm, K-feldspar exhibits elongate tabular habit</td>
<td>5 mm, some ovoid, tabular K-feldspar</td>
</tr>
<tr>
<td>Columns Present</td>
<td>No</td>
<td>Poorly developed in places</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Poorly developed in places</td>
<td>Well developed in places, cut by wedge-shaped sheeting joints</td>
</tr>
<tr>
<td>Follows proposed model from Hanson et al. (2014)</td>
<td>Yes</td>
<td>Yes</td>
<td>Partly</td>
<td>No</td>
<td>Difficult to determine</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Table 1.** Descriptive information for the different rhyolite flows in the WTH.
part, some section of the idealized Carlton Rhyolite schematic flow (Fig. 3). The following section will outline all terms that are used to describe individual flows and will also show representative photographs of relevant features.

**Flow Features**

**Basal Peperites**

Where exposed, the bases of flows in most cases show well-developed peperite, where the flows overlie tuffaceous mudstones as indicated in Plate I. The term peperite refers to a rock that develops during the interaction of lava or magma with unlithified, generally wet, sediments. The magma or lava quenches and breaks apart when it comes in contact with the wet material and is intermixed with the sediment (Skilling et al., 2002). This commonly results in the development of jigsaw texture (Figs. 7 and 8). The true thicknesses of peperite layers at the base of flows in the WTH are unknown due to outcrop limitations; however Hanson et al. (2014) note that, in most cases, peperite zones in the Carlton Rhyolite are <1 m thick.

**Glassy Chilled Margins**

Upper chilled margins are only exposed in the WTH in Flows 4 and 5; the lower margins of the flows crop out in Flows 1-4. Chilled flow margins are marked by zones of altered and devitrified glass. Rapid chilling formed silicic glass that subsequently became hydrated, producing perlitic texture (Fig. 9), which in some cases is the only indicator that the rock was at one time glass. Later alteration of the glass to Fe-rich green clays gives the rock a black to green-grey
Fig. 7. Hand sample of peperite at the base of Flow 3. Pink to grey rhyolite fragments rest in a matrix of dark brown tuffaceous mudstone. Examples of jigsaw texture are arrowed.

Fig. 8. Photomicrograph of thin section cut from hand sample depicted in Fig. 7. An example of well-developed jigsaw texture is outlined in yellow. Plane light; field of view ~1.3 cm across.
Fig. 9. Photomicrograph showing moderately developed onion-skin cracks defining perlitic texture from the glassy chilled lower margin of Flow 2. Groundmass consists of devitrified glass that is now a very fine grained quartzo-feldspathic intergrowth. Plane light; field of view ~4.25 mm across.
mottled appearance. The glass also underwent slow devitrification after cooling, forming very fine grained intergrowths of feldspars and quartz.

Within the glassy margins of the flows, small to large (<1 mm to >1 cm), irregular, flow-aligned and in some cases flow-elongated vesicles are present (Fig. 9). In some cases it is evident that either some vesicles have been stretched out so much that they were sheared into flow bands or vesicle nucleation occurred along the flow bands. These vesicles are either empty or filled partially or completely with silica and/or green clays.

**Spherulitic and Lithophysae-Rich Zones**

Lithophysae and spherulites in WTH rhyolites are commonly present in abundance just above the glassy chilled margins of flows. These features form during high-temperature devitrification of silicic lavas or welded ignimbrites. The lithophysae and spherulites commonly form in discrete zones <1 m thick, but in some cases small spherulites (<1 mm in diameter) form zones ≥ 10 m thick in the groundmass inward from the chilled margins. Spherulites in the WTH rhyolites occur as radiating quartzofeldspathic intergrowths (Fig. 10). In some flows the phenocrysts have spherulitic coronas (Fig. 10), but the spherulites mostly occur within the groundmass and in some cases have grown along flow lineations (Fig. 11).

Lithophysae typically include a central gas cavity surrounded by a spherulitic rim, which is composed of quartz and feldspar microlites, and delimited by a devitrification front. The cavities have cuspatelike shapes (Figs. 12 and 13) that record their formation near the glass-transition temperature during cooling (McArthur et al., 1998; Breitkreuz, 2013). In the WTH, lithophysae
**Fig. 10.** Photomicrograph of spherulites in groundmass of Flow 2. Yellow arrow points to a K-feldspar phenocryst which developed a spherulitic corona. Dark zones between spherulites are occupied by assorted opaque mafic grains (iron-oxides) and green clays. Clear areas in groundmass are secondary quartz. Note concentric zonation. Plane polarized light; field of view ~4.2 mm across.

**Fig. 11.** Hand sample of spherulites which grew along flow lineation in Flow 1.
Fig. 12. Hand sample from lithophysal zone in Flow 2. Note distinct light-colored spherulitic rims with central gas cavities. Groundmass that initially remained glass now has a dark brownish grey color.
**Fig. 13.** Close-up of hand sample shown in Fig. 12. An example of a gas cavity with cuspsate margins is outlined in yellow.
commonly are ~5-10 mm across. Larger lithophysae (30 cm in diameter) are documented in one flow in the Wichita Mountains (Bigger and Hanson, 1992).

The lithophysae in the WTH appear to have developed after the flow came to rest, as there is no elongation or distortion of their spherical shape. The gas cavities within the centers of the lithophysae are commonly lined with fine-grained, drusy quartz and/or chalcedony which was likely deposited from groundwater percolating through the rocks after volcanism ended.

**Flow Breccia, Flow Banding, and Flow Folding**

In the WTH rhyolites flow banding and flow folding commonly occur near the base of the flows just above or below the zones of spherulites and lithophysae and also are present near the top of Flow 4. The flow banding can be complicated and obscures phenocrysts and other groundmass features. It varies from a few centimeters thick down to fine-scale (<1 mm) lamina- tion defined by alternating dark-colored original glass and heterogenous pink to green felsite. The banding is generally parallel to the flow bases and is deformed by open to isoclinal flow folds that can be complex (Figs. 14, 15, and 16). Seaman et al. (2009) explain the development of flow banding in rhyolites as due to early, high-T devitrification of volatile-rich layers, possibly developed along discrete zones of shear. High volatile contents would speed up the devitrifica- tion rates in those layers, resulting in alternating layers of felsite and original glass.

Flow breccia in WTH flows is found at the base and top of flows and as discrete pockets within zones of flow banding and flow folding (e.g., Fig. 14). Generally outcrops of flow brecc- cia are limited in all but Flow 3, which is pervasively flow brecciated (Fig. 17). Interpretation of the available outcrops suggests that the formation of flow breccia involves the initial breakup of
Fig. 14. Outcrop photo from base of Flow 2 showing complex flow folding of flow bands and laminae. Dark zones are areas of original glass now altered to dark green clays. An isoclinal flow fold is seen to the lower right of the pencil tip.
Fig. 15. Flow fold outlined in yellow. Outcrop photo taken near base of Flow 2.
Fig. 16. Outcrop of an open flow fold in Flow 3 with pink pencil resting on fold hinge.

Fig. 17. Outcrop of well-developed flow breccia in Flow 3. Clasts are flow-banded and flow-laminated rhyolite that have broken apart and rotated during flow.
rigid flow bands due to high amounts of strain. These areas then can progressively evolve into zones of chaotic breccia that include rotated clasts showing varying degrees of fragmentation.

**Flow Interiors**

Generally, moving up section within an individual flow, the flow banding grades into a zone of heterogenous felsite marked by the appearance of a green to grey-pink mottled groundmass in hand sample. These zones show very small needle-like crystals in the groundmass in thin section (Figs. 18 and 19), interpreted to have originally been the high-temperature silica polymorph tridymite (now inverted to quartz). Continuing upwards within a flow, the groundmass becomes less mottled until it grades into a homogenous pink to orange felsite. By analogy with flows in the Wichitas (Hanson et al., 2014), these zones are thought to represent the most interior portions of the flows that underwent the slowest cooling.

In the flow interiors, tridymite needles are much larger than towards the base (Figs. 18 and 19). The needles are randomly oriented (Fig. 19), indicating that they started to grow once the flow came to rest. If the tridymite formed within its stability range, the random orientation means the flows came to rest above 870 °C (Deer et al., 2004). Although WTH flows were not sampled for thin section study continuously from base to interior, it is likely that the tridymite needles show uniform size increase towards the flow interiors, as is seen elsewhere in the SOA in flows that underwent slow, uniform cooling after being emplaced (Hanson and Eschberger, 2014).
Fig. 18. Photomicrograph from lower part of felsitic zone in Flow 1. Small needle-like crystals are interpreted to have been tridymite, now inverted to quartz. Plane light; field of view ~1.7 mm across.

Fig. 19. Photomicrograph from interior homogenous felsitic zone in Flow 1. Plane light; same scale as Fig. 18. Note that tridymite needles are much larger.
Columnar and Sheeting Joints and Flow Parting

Rhyolite flows in the WTH exhibit some degree of jointing related to cooling, including both columnar and sheeting joints. These features are indicated on Figure 6 and Plate I and are also seen elsewhere in the SOA (Hanson et al., 2014).

Columnar joints are common in volcanic rocks and form due to volume reduction during slow uniform cooling from the liquid state. Columns in the WTH are mostly poorly developed and obscured by other types of fractures such as sheeting or tectonic joints. This makes it difficult to measure the trend and plunge of columns. Table I shows in which flows columns are present and to what degree they are developed. When well-developed, columns range in size from 0.75-1.5 m across and have regular to irregular hexagonal shapes with ~120° angles between column faces (Figs. 20 and 21). Because these joints typically develop perpendicular to cooling surfaces, attitudes of the column long axes in some cases can give information on post-emplacement tilting that has occurred. In other places in the SOA, columns in the rhyolites are seen extending all the way from the base to top of flows (Hanson et al., 2014). However, columns in the WTH are generally only well represented in the flow interiors and towards the base and top of flows become obscured due to weathering, alteration, and other types of fractures.

Sheeting joints are less understood but are abundant in SOA rhyolites (Eschberger et al., 2014; Finegan and Hanson, 2014; Hanson et al., 2014). This term was originally applied to subparallel joints found within devitrified parts of large-volume Miocene A-type rhyolitic lava flows in the Snake River Plain, Idaho (Bonnichsen and Kauffman, 1987). In that area, the joints are only present in the felsitic interiors and absent near the glassy margins. Bonnichsen and Kauffman (1987) suggested that the joints develop during volume change due to devitrification of
Fig. 20. Scenic overlook of part of Flow 7 showing well-developed columns, some of which have slumped down in places. Trees are ~10m tall. Good examples of the columns are arrowed.

Fig. 21. Column in Flow 7, with column faces intersecting at ~120° angles. Wedge-shaped sheeting joints are also visible. Pink pencil for scale.
Sheeting joints in the WTH are also only present in the felsitic interiors, as in other parts of the SOA (Hanson et al., 2014).

In the WTH rhyolites, sheeting joints commonly overprint columnar joints in the interior of flows and can obscure the columns to the point where they can no longer be measured. The joints, on average, are spaced 0.5 to a few centimeters across and commonly intersect at wedge-shaped terminations against each other (Fig. 22). The sheeting joints tend to be perpendicular to the flow bases, similar to the columnar joints. More complex geometries shown by this type of jointing occur in some rhyolite outcrops in the Wichitas (e.g., Hanson et al., 2014).

**Descriptions of Individual Flows and Volcaniclastic Interbeds**

**Flow 1**

Flow 1 is the easternmost flow in the WTH. It is delimited to the south, east, and north by contacts with the overlying Reagan Sandstone. Much of the northern portion of this flow is affected by strong tectonic fracturing and part of the flow in the north (Fig. 6 and Plate I) is interpreted to be detached from the main flow by faulting. The faulted and fractured zones of the flow have pockets of cataclasite, and are so highly altered to green clays that groundmass features and phenocryst contents are mostly unrecognizable. The northern boundary of the flow is marked by part of the WVFZ, which juxtaposes the flow with Upper Cambrian to Lower Ordovician sedimentary units (Plate I). The base of Flow 1 rests on Interbed 1 to the west. Flow 1 is truncated by a present-day large valley in that area and is located directly east from Flow 2. The dip in this area is ~7° to the east-southeast based on bedding attitudes in the underlying interbed, and the valley here likely represents the original western extent of Flow 1, which was possibly in direct
Fig. 22. Remnant columns from Flow 7 that have been completely overprinted by wedge-shaped cooling joints. Pink pencil for scale, arrowed.
lateral contact with Flow 2, also resting on Interbed 1. A major fault runs northwest-southeast through Flow 1 and brings the base of the flow up in the western portion of the outcrop area relative to the middle of the flow to the east (Plate 1; Fig. 23).

As depicted in Table 1, Flow 1 has 10-15% phenocrysts which consist of K-feldspar, plagioclase and sparse mafic crystals replaced by green clays. The phenocrysts are subequant and are ≤7 mm in length. No good columnar joints were found in Flow 1. The flow is at least 65 m thick, although the true thickness is likely much greater as the top of the flow has been eroded away (Fig. 24). The bottom of the flow is exposed in one outcrop area at the western boundary, but is so highly altered that no original igneous textures are visible. The following portions of the generalized flow cross section (Fig. 3) are present here: lower glassy margin, lithophysal zone, in which the lithophysae are small (1-2 cm) and not abundant, overlying zone of flow banding and flow folding, and at least part of the homogenous felsitic center (Fig. 24). Tridymite needles coarsen upwards in the flow as well (Figs. 18 and 19). Locally there are zones of spherulites which appear to have developed on flow lineations (Fig. 11).

**Interbed 1**

Interbed 1 is a moderately thick (>15 m) sequence of volcaniclastic sandstones and tuffaceous mudstones, which is divided into three units labeled A, B, and C (Fig. 25). Unit A is ~10-12 m thick and is a dark grey to purple tuffaceous mudstone. It is characterized by thin planar bedding and lamination throughout (Fig. 26). Lenticular zones that have been altered to green clays and epidote occur in the lower portion of the unit. In the stratigraphically lowest outcrops these zones are 1-2 m in length, but decrease in size to 1-10 cm upward. In thin section, Unit A
Fig. 23. Cross section showing fault in Flow 1, lateral relations of Flows 1 and 2, and their relationships to Interbed 1.
Fig. 24. Generalized vertical section of Flow 1.
Fig. 25. Vertical section of Interbed 1 with Units A, B, and C labeled. Note decreasing abundance upward of silicic and basaltic shards in Unit A. Horizontal lines indicate planar bedding and lamination schematically.
**Fig. 26.** Middle portion of Unit A from Interbed 1 showing planar lamination.
contains very fine grained ash shards that are particle supported near the base with minor amounts of mud present, and become dispersed within a matrix of mud higher up. Originally glassy shards have been partly obliterated by diagenesis. Silicic bubble-wall and tricuspate shards and ash-sized pumice particles now replaced by quartz occur together with less abundant basaltic shards, which preserve spherical vesicles. The basaltic shards originally consisted of sideromelane, which was altered to palagonite and then later replaced by leucoxene (Figs. 27 and 28). The uppermost portions of Unit A show very few ash fragments and in thin section are dominated by abundant secondary epidote growth.

The upper few meters of Interbed 1 are marked by two distinctly different units. Unit B (~ 2 m thick) is a fine- to very fine grained, light tan to grey, planar-bedded, tuffaceous mudstone in hand sample with distinct layers (<3 cm thick) of subrounded coarser grained (1-2 mm) feldspar crystal fragments and rhyolitic lithic fragments, along with mud rip-up clasts ≤7 mm in length. In thin section the matrix between the grains is a mixture of fine-grained silicic and basaltic ash shards and terrigenous mud, similar to that present in Unit A, with an abundance of secondary epidote growth.

Unit C at the top of the interbed is a planner-bedded poorly sorted, pebbly to coarse-grained, subangular, volcaniclastic sandstone with abundant grains of felsitic rhyolite and K-feldspar showing varying degrees of alteration to sericite. These coarser grains are supported by a matrix of tricuspate silicic ash shards and minor amounts of mud.

The abundance of planar bedding and lamination and lack of tractional sedimentary structures leads to the inference that the interbed records settling of volcanic ash into a relatively quiet
Fig. 27. Photomicrograph of lower portion of Interbed 1, showing silicic tricuspate and bubble-wall shards now replaced by quartz. Plane light; field of view ~ 1.7 mm across.

Fig. 28. Photomicrographs of a basaltic ash shard showing spherical vesicles in Interbed 1, left in plane light, right in reflected light. White color in reflected light is indicative of leucoxene. Fields of view ~ 0.7 mm across.
lacustrine environment. Coarser grained beds in the upper part of the interbed are interpreted to have been deposited from sediment gravity flows coming into the lake.

**Flow 2**

Flow 2 is the next flow to the west in the field area and is the most extensively exposed in terms of lateral extent and thickness. The eastern boundary of the flow has been discussed above. Its southern boundary is overlain by the Reagan Sandstone. The northern boundary is marked by the WVFZ, where Flow 2 shows similar degrees of alteration and fracturing as seen in the northern portion of Flow 1. A large debris-flow deposit truncates the western portion of Flow 2 and fills a paleovalley that cuts into it, as discussed below.

Flow 2 has 15-20% phenocrysts consisting of K-feldspar, plagioclase, and mafic crystals replaced by green clays. Mafic phenocrysts occur in higher amounts than in the other flows and some of these phenocrysts were originally fayalite, based on crystal habit and relict conchoidal fracture (Fig. 29). K-feldspar phenocrysts have elongate tabular shapes with ovoid outlines.

Flow 2 is at least 80 m thick, and the top of the flow is presumed to have been lost due to erosion. The following portions of the generalized rhyolite cross section are present (Fig. 30): peperite with perlitic rhyolite clasts (Fig. 31), lower glassy margin, showing perlitic texture (Fig. 9), lithophysal zone which exhibits larger (2-5 cm) and more abundant lithophysae than in Flow 1 (Figs. 12 and 13), flow-banded zone (Figs. 14 and 15), and a homogenous felsitic center with tridymite needles coarsening upwards. Flow 2 also shows spherulites ~1-2 mm in diameter (Fig. 10) that are abundant near the lithophysal zone. The flow has poorly developed columns in some locations (generally present in the felsitic zones) (Plate I).
Fig. 29. Photomicrograph from Flow 2 showing glomerocryst consisting of plagioclase (P) and mafic crystals that have been replaced by green clays and magnetite. Mafic crystals show relict conchoidal fractures (arrowed), suggesting that they were originally fayalite. Field of view ~1.7 mm; plane light.
Fig. 30. Generalized vertical section of Flow 2.

Fig. 31. Basal peperite in Flow 2 outcrop. Pencil for scale. Brown colored fragments are originally glassy rhyolite showing perlitic texture in thin section. White material is sediment. An example of jigsaw texture is arrowed.
**Flow 3**

The eastern boundary of Flow 3 is marked by a Cambrian debris-flow deposit as well as a present-day valley, partly filled with colluvium and alluvium. The southern boundary is in normal stratigraphic contact with the overlying Reagan Sandstone and is partially cut by a massive polymict igneous breccia (Toews, 2015). The western boundary is delimited by a large present-day valley which is also partly filled with colluvium. The northern boundary is in stratigraphic contact with underlying Interbed 2. Flow 3 is markedly different from Flows 1 or 2 in that it shows flow banding, flow folding (Fig. 16), spherulitic textures, and flow breccia (Fig. 17) throughout the exposed portion.

Flow 3 has ~10% phenocrysts made up of K-feldspar and some mafic crystals. K-feldspar crystals are tabular and ≤ 2 cm long. No columns were found to be present in the exposed portions of this flow. The flow is at least 60 m thick, but only the lower part of the flow appears to be present (Fig. 32). Peperite occurs at the base (Figs. 7 and 8), followed by the lower glassy margin, which passes up into rhyolite with a green and pink mottled groundmass as shown in Figure 32. There is no lithophysal zone, but there is a discrete zone of spherulites 1-2 cm in diameter that occurs roughly where the lithophysal zone would be expected.

**Interbed 2**

Interbed 2 is not well exposed, separates the base of Flow 3 from the top of Flow 4, and is ~20-25 m thick. In hand sample, portions of Interbed 2 are a waxy, very fine grained, tuffaceous mudstone that weathers to a brownish orange and is dark grey to purple on a fresh surface; in places a well-defined planar lamination is present (Fig. 33). Beds ~1 m thick of coarse-grained
Fig. 32. Generalized vertical section of Flow 3.
volcaniclastic sandstone, which is tan to light grey on a fresh surface, are intercalated with the mudstone. The sandstone beds in some cases show tractional current structures such as trough cross-bedding. Because of poor exposure, it was not possible to document this interbed thoroughly. It is generally highly altered and difficult to distinguish from the rhyolite flow above it.

**Flow 4**

Flow 4 is the only nearly complete exposed flow in the WTH and is also the thinnest at 20 m (Fig. 34). It is very different from the other flows in that it shows no lithophysae, spherulites, or tridymite needles and has a very low phenocryst content (<2%), with both K-feldspar and plagioclase present. No columns are visible. Its outcrop is limited to the west and east by colluvium and alluvium. The base of the flow is interpreted to rest on Flow 5, although no outcrops show this contact.

The top portion of Flow 4 is pervasively flow brecciated and flow banded and is generally greatly affected by secondary alteration, including heavy sericitization of feldspars. The flow has large, irregularly shaped vesicles (10-20 cm in diameter) (Figs. 35 and 36), that are partially filled with quartz and chalcedony. The vesicles appear ~5 m from the top boundary of the flow and disappear ~10 m into the flow interior. The bottom portion of the flow is flow banded and finely laminated with local flow breccia. This flow does not seem to follow the Hanson et al. (2014) model, possibly because it is so thin that uniform cooling features did not develop as they would in the thicker flows.
Fig. 33. Outcrop of Interbed 2 showing well-developed lamination. Pencil for scale
Fig. 34. Generalized vertical section of Flow 4.
Fig. 35. Hand sample of large irregular vesicles, outlined in yellow, near the top of Flow 4.

Fig. 36. Photomicrograph of vesicles similar to those depicted in Fig. 35. Note irregular shapes and perlitic texture that has developed in the adjacent groundmass. Vesicles are filled with quartz and chalcedony. Plane light; field of view ~1.3 cm across.
Flow 5

Only the very top of Flow 5 is reasonably well exposed and is interpreted to be in direct contact with Flow 4 to the south. Because only limited good outcrops of this flow are present, a schematic vertical section is not shown for it. Although the contact is covered, there is an abrupt change in phenocryst content from nearly aphyric in Flow 4 to 5-10% K-feldspar phenocrysts in Flow 5 (Table 1), and groundmass color changes from yellow-orange in Flow 4 to dark pink to grey in Flow 5. This along with the occurrence of an upper flow breccia in Flow 5, leads to the interpretation that a flow boundary is present. This flow is delimited to east and west by alluvium or colluvium. Moving northward, the lower portion of the flow is cut by hypabyssal intrusions and affected by tectonic overprinting defined by zones of closely spaced fractures and abundant cataclasite, with quartz veinlets common in hand sample. The tectonic overprint makes seeing volcanological features and phenocrysts difficult. The northern extent of this flow is likely marked by the Washburn Ranch Fault (Fig. 6 and Plate I), although the contact is covered. The flow top has small pockets of flow breccia and fine-scale flow banding with some spherulites present below the flow bands. No good columns were found in the outcrop exposures.

Flow 6

Moving northward from Flow 5 across the Washburn Ranch Fault, the field area becomes dominated by hypabyssal intrusions and masses of polymict igneous breccia. I was able to map one partial flow in this area, termed Flow 6. The outcrop for this unit is very limited and so there is no generalized vertical section. However, where the flow is exposed it exhibits a spherulitic groundmass in the lower part that grades into a mottled green to grey-pink heterogenous
groundmass upward. In the uppermost exposed portions of this flow, a nearly homogenous
groundmass is present. The flow was discovered very late in the course of mapping and no thin
sections have yet been made. Flow 6 has 5-10% K-feldspar phenocrysts ranging in size up to 1 cm, some of which have an elongated tabular habit similar to those present in Flow 3. The exposed thickness of this flow is ~50 m. A small portion of the flow near the Washburn Ranch Fault is highly fractured and altered.

**Flow 7**

Flow 7 is the westernmost rhyolite flow exposed in the WTH. It is separated from the rest of the flows by a major unnamed fault, extensive hypabyssal intrusions, and discordant masses of igneous breccia. The southern boundary of Flow 7 is marked by the Washburn Ranch Fault, which juxtaposes the rhyolite against Arbuckle Group strata. The western and northern extents are defined by the unconformity with the overlying Reagan Sandstone. Flow 7 has 15-20% phenocrysts, consisting of K-feldspar, plagioclase and sparse mafic crystals now replaced by green clays. The available outcrops of Flow 7 appear to represent only part of the homogenous felsitic center of a much thicker flow (Fig. 37). As depicted in Figures 20, 21, and 22, the flow has well-developed columns which are cut by wedge-shaped sheeting joints. Tridymite needles coarsen upwards in the flow, and a zone of small (0.5-2 mm) spherulites near the base of the exposed outcrops suggests that the glassy basal margin of the flow is in close proximity.
**Flow 7**

- Top not exposed
- Homogeneous felsitic center
- Spherulitic zone
- Bottom not exposed
- At least 60 m
- Tridymite needles coarsening upwards

*Fig. 37. Generalized vertical section of Flow 7.*
**Debris-Flow Deposit**

A debris-flow deposit occurs within the Carlton Rhyolite in the middle southeastern part of the WTH (Fig. 6 and Plate I) and is at least ~45 m thick although the base is not exposed. The deposit is massively bedded and very poorly sorted with rhyolite clasts ranging up to 4.2 m across. The coarse clasts are angular to subrounded and are supported by a finer grained clastic matrix (Fig. 38). The clasts consist dominantly of different lithologies of rhyolite, with phenocryst contents ranging from 5-20%. Some of the larger rhyolite clasts appear to be part of columns (Fig. 39). Clasts of amygdaoidal basalt ≤ 10 cm in length are less abundant (Fig. 40) and are highly altered. The finer matrix of the deposit typically consists of angular to subrounded, coarse sand- to silt-sized clasts of the same rock types as the coarser clasts, together with brown terrigenous mud. Some portions of the debris-flow deposit include rounded mudstone rip-up clasts ranging in size from 5 mm to a few centimeters in length.

The mapped relations indicate the debris-flow deposit occupies a steep-walled paleochannel trending north to northeast that was cut into Flows 2 and 3. Large tabular clasts (up to 4.2 m) of flow-banded rhyolite similar in lithology to Flow 3 occur in the exposed upper part of the debris-flow deposit near its boundary with that flow. Large clasts (up to 3 m) were also found near the contact with Flow 2 (Fig. 39) and are lithologically similar to that unit. These observations suggest the two rhyolite flows were contributing detritus to the debris flow as it traveled down the channel. A geochemical analysis of one of these clasts is included in Chapter 5.

One unusual thing about this debris-flow deposit is that it contains peperitic domains ~1 m across where rhyolite clasts are separated by partially disrupted terrigenous mud, sand, and silt, which partially preserve original sedimentary lamination (Figs. 41 and 42). Rhyolite clasts in
Fig. 38. Hand sample of typical texture of debris-flow deposit, with muddy matrix and varying sizes and shapes of rhyolite clasts of different types.
Fig. 39. Outcrop showing one of the larger clasts of rhyolite found within the debris-flow deposit. A chemical analysis of this clast is given in Chapter 5.
Fig. 40. Outcrop of debris-flow deposit, with tip of pencil pointing to basalt clast.
Fig. 41. Outcrop of peperitic domain within debris-flow deposit, with partly preserved lamination (L) in host sediment that wraps around larger clasts. One small zone of fine-scale peperite is arrowed.
Fig. 42. Outcrop of debris-flow deposit. Clasts of rhyolite have interacted in a fluidal manner with the sediment (circled).
these domains show fluidal interaction with the sediment and in situ fragmentation of quenched lava defined by jigsaw textures.

The debris-flow deposit is tentatively interpreted as the result of a series of events. Sediment initially accumulated on an unstable slope somewhere upstream. A rhyolite lava flowed onto the wet sediment, loading it and interacting with the sediment at the base of the flow. Eventually the slope became destabilized, causing slumping that developed into a debris flow which then incorporated additional clasts and sediment as it flowed down the preexisting channel.
CHAPTER 5: GEOCHEMISTRY

Introduction

Major and trace element analyses were performed on twelve whole-rock samples from rhyolites in the WTH. The analytical data are shown in Appendix I and sample locations are indicated on Plate 1. Samples were taken vertically through flows where outcrop exposure permitted. It was not possible to collect good unaltered samples throughout parts of the field area due to closely spaced tectonic fractures or alteration. Three samples were collected from Flow 1, five from Flow 2, one from a rhyolite clast in the debris-flow deposit, one from Flow 3, and two from Flow 7. A reliable sample could not be collected from Flow 4 as it was too highly altered, and Flows 5 and 6 were discovered too late in this project to receive data back within a reasonable time frame for completion of the thesis.

Petrographic analyses indicate that the samples are altered to varying degrees, and loss on ignition (LOI) varies from 0.84 to 2.51 wt %. The most common type of alteration product is silicification, evidenced by veinlets filled with quartz and chalcedony, followed by replacement of mafic phenocrysts with green clays. Additional vein-filling minerals include fluorite, calcite, and dolomite. Veins and amygdules were avoided during sample collection and preparation, but were difficult or impossible to remove in some cases. Secondary silica is especially evident in samples 98 and 100, which were collected from an alteration zone in Flow 2, and contain veins and vesicles partially to completely filled by chalcedony or drusy quartz (Figs. 43 and 44). Alteration is most pronounced in sample 98, and both this sample and sample 100 were analyzed to help constrain the affects of alteration on the geochemistry of the rocks. Flow 2 also had the
Fig. 43. Photomicrograph from geochemical sample 98 from Flow 2 showing abundant secondary silica growth and high degrees of alteration of feldspars. Plane polarized light; field of view ~1.7 mm.

Fig. 44. Photomicrograph from geochemical sample 100 from Flow 2 showing silica veins and alteration of feldspars. Plane polarized light; field of view ~0.7 mm.
highest LOI values, which correlate with its high degree of alteration.

**Major Elements**

Figures 45-52 are Harker variation diagrams for major elements in rhyolite flows from the WTH. Data from the upper and lower rhyolite flows in the ETH are also shown in these figures and are taken from Eschberger et al. (2014). WTH rhyolites range in silica content from 68.77-75.15 wt %. Samples from Flows 1, 3, and 7 generally plot relatively close together on the Harker diagrams. Four of the five samples of Flow 2 have the lowest silica contents of all analyzed flows. The wide compositional variation shown by this flow in Harker variation diagrams is attributed to secondary silicification, as the two samples with the highest silica contents in that flow are 98 and 100, discussed above. Some of the ETH rhyolites are more fractionated than WTH samples, but several samples from the upper flow from the ETH plot close to samples collected from Flows 1, 3, and 7 on the diagrams. Toews (2015) shows that microgranites from the WTH are less differentiated than most of the WTH flows, but plot close to Flow 2 samples.

Generally, samples exhibit high Fe/MgO ratios and low MgO and CaO contents (Appendix I), which are normal features of A-type felsic rocks (Whalen et al., 1987; Eby, 1990). TiO₂, P₂O₅, CaO, MgO, and FeO all decrease with increasing silica contents. These are typical igneous trends, commonly attributed to the fractionation of titanomagnetite, apatite, plagioclase, and mafic silicates during magma evolution.

K₂O and Na₂O mostly show scatter (Figures 50 and 51). This reflects high alkali mobility during alteration. Two samples from Flow 2, the debris-flow clast, and one sample from Flow 6 all plot to the right of the normal igneous spectrum (Hughes, 1972) in Figure 53, which indicates
Fig. 45. Harker variation diagram for TiO$_2$. 

**Explanation of Symbols**

**West Timbered Hills**
- ○ Flow 1
- △ Flow 2
- ▲ Flow 3
- ★ Flow 7
- ○ Debris-Flow Clast

**East Timbered Hills**
- ★ Upper Rhyolite Flow
- △ Lower Rhyolite Flow
**Fig. 46.** Harker variation diagram for Al$_2$O$_3$.

**Fig. 47.** Harker variation diagram for FeO.

**Fig. 48.** Harker variation diagram for MgO.
Fig. 49. Harker variation diagram for CaO.

Fig. 50. Harker variation diagram for Na₂O.

Fig. 51. Harker variation diagram for K₂O.
Fig. 52. Harker variation diagram for $P_2O_5$. 
the samples experienced a significant gain in K₂O and loss Na₂O during alteration. In WTH flows, sericite is seen replacing feldspars in all flows, providing petrographic evidence for alkali mobility, although no correlation between degree of sericitization in thin section and K₂O values could be determined. Some of the scatter seen in the other Harker diagrams could also be a result of alteration.

**Trace Elements**

*Harker Diagrams and Ta/Th vs Ti/Zr diagram*

Harker diagrams for selected trace elements are shown in Figures 54-59. Both Sc and Sr decrease with increasing silica contents (Figs. 54 and 55). Sc is fairly resistant to alteration (Rollinson, 1993), so this correlation likely reflects a primary igneous trend. Sc is compatible with pyroxene and titanomagnetite (Mahood and Hildreth, 1983; Rollinson, 1993) and therefore the Sc depletions probably represent the fractionation of one or both of these phases. The trend for Sr is consistent with plagioclase fractionation, although the data are somewhat scattered, presumably reflecting disturbance of Sr during alteration. In contrast Rb shows no obvious trends (Fig. 56), reflecting significant secondary disturbance of the alkalies in these rocks.

Figures 57-59 show Harker variation diagrams for Zr, Th, and Nb, which are relatively immobile during alteration (Pearce and Cann, 1973; Winchester and Floyd, 1977; Rollinson, 1993). Concordant with findings in the ETH (Eschberger, 2012; Eschberger et al., 2014), rhyolites in the WTH show no obvious trends on these diagrams. Eschberger (2012) showed that felsic igneous rocks in the ETH plot in three main groups, as shown in Figure 57. Most of the data for the WTH rhyolites fall within the Group 1 field from Eschberger (2012). In the Harker dia-
Fig. 53. Igneous spectrum diagram of Hughes (1972). One sample from the lower rhyolite flow in the ETH is not shown because it plots off the range of the diagram.

Fig. 54. Harker variation diagram for Sc.

Fig. 55. Harker variation diagram for Sr.
Fig. 56. Harker variation diagram for Rb.

Fig. 57. Harker variation diagram for Zr showing three distinct chemical groups described by Eschberger (2012). Groups 2 and 3 come from hypabyssal intrusions.

Fig. 58. Harker variation diagram for Th. Geochemical groups shown by WTH rhyolites are outlined.
grams for Th and Nb (Figs. 58 and 59), samples from Flow 1, Flow 7, Flow 3, the debris-flow clast, and three samples from Flow 2 all plot in distinct geochemical groups. Samples from Flow 7 tend to plot either near or with the upper flow samples from the ETH. The same groups are especially obvious in the Ti/Zr vs Ta/Th diagram in Figure 60. Fields for rhyolites exposed in the Wichita Mountains are also shown in that figure (Hanson et al., 2014). Data from the WTH show little correlation with these fields. The trace-element diagrams provide strong evidence that individual flows in the WTH were sourced from geochemically distinct magma batches that cannot be related directly by fractional crystallization.

**Rock Classification and Magmatic Affinities**

Because of the evidence that the major elements have been disturbed to varying degrees during alteration, immobile trace elements were used when classifying these rocks. Figure 61 shows data for the rhyolites in the WTH and ETH plotted on a discrimination diagram developed by Winchester and Floyd (1977), which relies on ratios of immobile minor and trace elements. Most of the data plot in or just outside the rhyolite field. Individual flows mostly plot together except for sample 100 from Flow 2 (arrowed in Fig. 61) which was highly altered. Flow 1, 3, and the debris-flow clast plot inside the peralkaline field, while Flow 2 plots just inside the trachyan-desite field. Flow 7 and sample 100 from Flow 2 plot within the rhyolite field.

Figure 62 shows Zr plotted vs $10^4$Ga/Al on a discrimination diagram developed by Whalen et al. (1987). The diagram indicates that all the analyzed rhyolite flows within the Arbuckle Mountains have A-type compositions. Figure 63 shows the Nb vs Y discrimination diagram from Pearce et al. (1984), which indicates that all felsic samples in the Arbuckles have within-plate granite signatures.
**Fig. 59.** Harker variation diagram for Nb. Geochemical groups shown by WTH rhyolites are outlined.

**Fig. 60.** Ta/Th vs. Ti/Zr diagram. Groups from Hanson et al. (2014) are shaded in blue. Geochemical groups shown by WTH rhyolites are outlined.
Fig. 61. Discrimination diagram after Winchester and Floyd (1977). Sample 100 is arrowed.
Fig. 62. Zr vs. $10^4$Ga/Al discrimination diagram of Whalen et al. (1987).

Fig. 63. Nb vs Y discrimination diagram of Pearce et al. (1984).
Normalized Multi-Element and REE Diagrams

The rhyolite samples are plotted on a multi-element diagram in Figure 64, which has been normalized to primitive mantle data. All samples show negative anomalies in Sr, Eu, P, and Ti, consistent with the fractionation of plagioclase, apatite, and titanomagnetite. Fractionation patterns of this type are commonly shown by A-type felsic rocks. Flow 2 shows the least depletion in Sr, P, and Ti, consistent with its generally less fractionated major element compositions. Small depletions in Nb and Ta are shown by the samples, indicating the magmas interacted to some degree with continental lithosphere previously modified by subduction (e.g., Pearce, 1982).

Rare earth elements (REE) are resistant to alteration and therefore prove useful in studying altered igneous rocks. Figure 65 shows REE data for all samples. There is a general trend of depletion in the heavy rare earth elements (HREE), and enrichment in the light rare earths (LREE). All samples show a negative Eu anomaly, and some also show a negative Ce anomaly. The negative Eu anomaly reflects fractional crystallization of plagioclase and the negative Ce anomaly is likely due to alteration (e.g., Seifert et al., 1985). However, the degree of Ce depletion shows no obvious correlation with petrographic evidence for different degrees of alteration visible petrographically.

Flows from the ETH are generally more fractionated than the flows from the WTH in Figure 64, consistent with trends seen in the Harker diagrams. Light REE data for the ETH flows shows a wider variation than the WTH samples, and the ETH samples are less depleted in heavy REEs. Note a negative Ce anomaly is also present in some ETH samples.
**Fig. 64.** Multi-element diagram for rhyolite flows in the Arbuckle Mountains. Normalization values from Sun and McDonough (1989). ETH data shown as blue field.

**Fig. 65.** REE diagram for rhyolite flows in the Arbuckle Mountains. Normalization values from Sun and McDonough (1989). ETH data shown as blue field.
Other Discrimination Diagrams

Figures 66-68 are discrimination diagrams developed for A-type felsic rocks by Eby (1990, 1992). These diagrams can only be applied to samples which plot within the A-type field in Figure 62. Figures 65 and 67 are divided into two areas, A1 and A2. The A1 field represents felsic magmas which were derived from OIB-type sources in intraplate settings, including continental rift zones or hot-spot settings. The A2 field represents felsic magmas that were derived from sources previously modified by arc magmatism (Eby, 1992). Samples from Flow 1 plot within A1 fields on both diagrams. All other samples from the WTH and ETH plot in the A2 fields.

In Figure 68, most Arbuckle rhyolite samples plot between the OIB field and fields for syn-collisional granite and volcanic arc granites. Data from the Wichita Mountains rhyolites have been shaded in grey and show a similar trend. The simple explanation for these data is that the rocks record production of magmas from OIB sources with varying degrees of interaction of these magmas with older crust. In general ETH samples indicate a higher degree of interaction of the magmas with older crust than the WTH samples. An exception is Flow 7 which plots with the ETH data. Flow 1 plots within the OIB field and likely represents magma which experienced little interaction with older crust.
Fig. 66. Nb-Y-Ce Discrimination diagram for A-type felsic rocks developed by Eby.

Fig. 67. Y-Nb-Ga Discrimination diagram for A-type felsic rocks developed by Eby (1992).
Fig. 68. Ce/Nb vs Y/Nb diagram developed by Eby (1990). MORB: mid-ocean ridge basalts; IAB: island-arc basalts; C: average crustal ratios; CG: syn-collision granite; VAG: volcanic arc granite; OIB: ocean island basalts.
Mapping of extrusive units within the Carlton Rhyolite Group in the WTH has revealed seven different rhyolite flows, two sedimentary interbeds which separate some of the flows, and an unusual debris-flow deposit. These units are cut by hypabyssal diabase and microgranite intrusions and discordant masses of polymict igneous breccia (Toews, 2015).

The flows crop out over an area of ~10 km² and exposed thicknesses of individual flows range from 20-80 m. Flows generally show vertical zonations starting with a glassy chilled lower margin which develops basal peperite in some cases. Flow banding and flow breccia zones are also present in the lower parts of the flows but disappear higher up. Zones of spherulites and lithophysae occur within the glassy chilled margins, which grade upwards into a homogenous felsitic center where randomly oriented groundmass tridymite needles first appear and then increase in size towards flow interiors. The zonations seen here in the WTH are consistent with the model developed by Hanson et al. (2014) for flows exposed in the Wichita Mountains and indicate that the WTH flows were emplaced as simple cooling units. A lateral contact occurs between two of the flows in the WTH, which is the first such contact recognized in the Carlton Rhyolite Group.

The two sedimentary interbeds have exposed thicknesses of ~15-25 m and contain planar-laminated tuffaceous mudstones that consist of silicic and less abundant basaltic ash shards intermixed with terrigenous mud. These units are inferred to have been deposited in quiet lacustrine environments. Coarser interbedded volcaniclastic sandstones represent sediment gravity-flow deposits.
Tuffaceous material in the sedimentary interbeds records some pyroclastic activity in the SOA, possibly at considerable distances from the site of deposition. There is little evidence for major pyroclastic eruptions in the WTH, consistent with other work on the Carlton Rhyolite Group (Hanson and Eschberger, 2014; Puckett et al., 2014). Rhyolites throughout the SOA were erupted primarily as non-explosive lava flows. The consistent vertical zonation found in almost all the flows suggests that the present outcrops may be remnants of laterally extensive flows similar to those found in other A-type volcanic provinces (e.g., Henry et al., 1990; McPhie et al., 2008).

Map relations show that a debris-flow deposit in the WTH occupies a steep-walled paleo-valley carved into two of the flows. The deposit is at least 45 m thick and contains clasts up to 4.2 m across. Clasts include both basalt and different types of rhyolite. Peperitic domains occur in parts of the deposit where clasts are separated by disrupted terrigenous mud and sand that partially preserve original sedimentary lamination. The debris flow is interpreted to have been produced when rhyolite lava flowed on top of sediments on an unstable slope causing slope failure, which produced a chaotic flow with partially molten portions that interacted to varying degrees with wet sediments on the slope or within the valley.

Geochemically all the rhyolite flows sampled in the Arbuckle Mountains show A-type affinities, which is consistent with findings elsewhere in the SOA (Hanson and Eschberger, 2014; Puckett et al., 2014). Mobile trace and major elements appear to been disturbed to various degrees during alteration. However, Harker variation diagrams for TiO$_2$, P$_2$O$_5$, CaO, MgO and FeO all show trends consistent with the fractionation of titanomagnetite, apatite, and mafic silicates.
Individual flows generally plot together on trace-element discrimination diagrams using immobile elements, indicating that the flows represent geochemically distinct magma batches, possibly derived from separate chambers or sources. There is little correlation between data fields for the Arbuckle flows and fields given by Hanson et al. (2014) for rhyolites exposed in the Wichita Mountains, indicating that flows from the WTH and Wichitas were erupted from separate, geochemically distinct sources or magma reservoirs.

Geochemical data plotted on discrimination diagrams developed by Eby (1990, 1992) show that the WTH rhyolite magmas were likely derived from OIB sources and underwent varying degrees of interaction with pre-existing crust. The geochemical database for the WTH rhyolite flows is limited and more work could be done in this area, including isotopic studies to better constrain magma sources.
Appendix I: Geochemical data for rhyolite flows in the Arbuckle Mountains

Normalized major elements (wt. %)\(^a\)

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<tr>
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<tr>
<td>SiO(_2)</td>
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<tr>
<td>TiO(_2)</td>
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<tr>
<td>Al(_2)O(_3)</td>
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<td>FeO(^b)</td>
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<td>MnO</td>
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<td>Na(_2)O</td>
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<td>K(_2)O</td>
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<td>LOI(^c)</td>
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<tr>
<td>Total(^d)</td>
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Trace elements (ppm)

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\(^a\) - Normalized to 100% on a volatile-free basis. \(^b\) - Total Fe reported as FeO. \(^c\) - Loss on ignition. \(^d\) - Total before normalization.
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**Trace elements (ppm)**

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a - Normalized to 100% on a volatile-free basis. b - Total Fe reported as FeO. c - Loss on ignition. d - Total before normalization.
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ABSTRACT

VOLCANIC LITHOFACIES AND GEOCHEMISTRY OF CAMBRIAN RIFT-RELATED RHYOLITES IN THE WEST TIMBERED HILLS, ARBUCKLE MOUNTAINS, SOUTHERN OKLAHOMA

by Joseph Robert Boro, M.S., 2015
School of Geology, Energy and the Environment
Texas Christian University

Thesis Advisor: Dr. Richard Hanson, Professor of Geology

The Cambrian Carlton Rhyolite group forms the uppermost main unit in a major rift fill sequence in southern Oklahoma. The rhyolites crop out in the Wichita and Arbuckle Mountains. The most extensive outcrops in the latter area occur in the West Timbered Hills. My project is the first detailed volcanological and geochemical study of the West Timbered Hills rhyolites. The rhyolites there have similar A-type affinities to felsic rocks elsewhere in the southern Oklahoma rift. Seven rhyolite lava flows separated in places by sedimentary interbeds and a thick debris-flow deposit filling a paleochannel have been identified. The lava flows show a standard vertical zonation indicating they were erupted as non-explosive, simple cooling units, and the outcrop exposures may be remnants of laterally extensive flows similar to those seen in some other A-type provinces.