PHYSICAL VOLCANOLOGY AND GEOCHEMISTRY OF THE CAMBRIAN
CARLTON RHYOLITE IN THE FORT SILL AREA,
SOUTHWESTERN OKLAHOMA

by

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CHAPTER 1: INTRODUCTION

General Setting and Research Goals

Located in southwestern Oklahoma, the Wichita Mountains are the surface expression of a much larger basement complex consisting primarily of a bimodal suite of intrusive and extrusive igneous rocks that are collectively known as the Wichita province (Fig. 1; Ham et al., 1964). Igneous rocks of the province were emplaced during Neoproterozoic to early Cambrian rifting associated with continental breakup along the southeastern margin of Laurentia. Felsic rocks dominate surface exposures in the region (Fig. 1), including voluminous volcanic rocks of the Carlton Rhyolite Group, which forms the upper portion of the igneous rift fill. Extensive granites with sheet-like geometries of the Wichita Granite Group intrude lower parts of the volcanic pile (Ham et al., 1964; Hogan and Gilbert, 1997; Hanson et al., 2013). Felsic rocks of the province show A-type affinities in the sense of Loiselle and Wones (1979); that is, they represent anhydrous felsic magmas emplaced in an anorogenic setting (Myers et al., 1981; Weaver and Gilbert, 1986; Hogan and Gilbert, 1997; Hogan et al., 2000; Hanson et al., 2013).

Exposures of the Carlton Rhyolite Group in southwestern Oklahoma are limited to four general areas in the Wichita Mountains (Fig. 1), with additional outcrops of rhyolite occurring ~130 km to the southeast in the Arbuckle Mountains. Within the Wichita Mountains, several exposures of Carlton Rhyolite occur on isolated hills, north of the main igneous mass, in an area known as the Slick Hills. There, the rhyolite crops out on Zodletone Mountain, Bally Mountain, and in the Blue Creek Canyon area (Fig. 1). To the south, within the main igneous mass of the Wichita Mountains, the most extensive rhyolite exposures occur in the Fort Sill area (Fig. 1). TCU workers have done substantial research on Carlton Rhyolite exposures in the Slick Hills.
Figure 1. Geologic map of the Wichita Mountains. Area shown in Plate I and Figure 4 is indicated. Modified from Powell et al. (1980).
(Bigger and Hanson, 1992; Philips, 2002; Burkholder, 2005; Hanson et al., 2014) and in the Timbered Hills area in the Arbuckle Mountains (Eschberger, 2012; Eschberger et al., 2014; Boro, 2015; Toews, 2015), while outcrops in the Fort Sill area have never received detailed attention. The present study therefore focuses on exposures of Carlton Rhyolite in the Fort Sill area, where extensive (~30 km²) outcrops of the Carlton Rhyolite Group occur. Only general geologic mapping has been done in the Fort Sill area (Schoonover, 1948), with little detailed attention placed on the volcanology and internal stratigraphy of the Carlton Rhyolite there. Some general aspects of the regional geology in the Fort Sill area are also poorly understood, including contact relations between the rhyolite and adjacent, intrusive granite, contact metamorphism of the rhyolite caused by granite intrusion, and brittle deformation of the rhyolite.

The main flow unit in the Fort Sill area (the Fort Sill rhyolite), as well as some units in the Slick Hills, shows similarities to laterally extensive units that have been documented worldwide from other intraplate, A-type felsic provinces. Some of these areas include the Bushveld Complex, South Africa (Twist and French, 1983), Trans-Pecos Texas (Henry et al., 1988, 1990; Henry and Wolff, 1992), the Keweenawan Supergroup, Minnesota (Green and Fitz, 1993), the Gawler Range, South Australia (Creaser and White, 1991; Allen and McPhie, 2002), the Etendeka province, Namibia (Milner et al., 1992), Paraná basin, South America (Kirstein et al., 2001), and the Snake River Plain, western United States (Bonnichsen and Kauffman, 1987; Manley, 1995, 1996a, 1996b; Branney et al., 2008). Particularly well-documented, single large flows of this type include the Bracks Rhyolite in Texas (Henry et al., 1990) and the Eucarro Rhyolite in Australia (Allen and McPhie, 2002), where the preserved lengths can be traced for ~55 km and ~225 km, respectively.
Such deposits are highly controversial and have received much attention recently from volcanologists. The main debate is whether these deposits represent laterally extensive large-volume lava flows erupted in a nonexplosive manner, or whether they are rheomorphic ignimbrites that have undergone secondary viscous flowage and homogenization, destroying evidence of a pyroclastic origin. Distinguishing between the two types of deposits is important for understanding eruption and flow mechanisms, interpreting ancient felsic volcanic successions, and assessing potential volcanic hazards.

The main goals of this study are: 1) to map the Carlton Rhyolite in the Fort Sill area, 2) to provide detailed descriptions of the volcanic stratigraphy and internal characteristics of individual units of the Carlton Rhyolite Group in the area, 3) to determine contact relations between units of the Carlton Rhyolite Group and intrusive granite, and 4) to characterize the geochemical composition of the Carlton Rhyolite Group in the area. One main problem to be addressed is whether the rhyolites in the Fort Sill area were erupted explosively and emplaced as rheomorphic ignimbrites, or were erupted nonexplosively and emplaced as coherent lava flows. Additional key points to determine are if the rhyolites in the Fort Sill area have the same A-type geochemical characteristics as Carlton Rhyolite in the Slick Hills and the Wichita granites, and whether they show evidence of a related petrogenetic history. Initial results of this study have been presented in Finegan and Hanson (2014).

**Methods of Study and Analytical Techniques**

The principal research methods used to document the Carlton Rhyolite in the Fort Sill area included detailed field mapping, petrographic analyses, modal analyses, and major- and trace-element geochemical analyses. Each method is discussed in more detail below.
Field Mapping

The distribution of the Carlton Rhyolite Group in the Fort Sill area was constrained by mapping individual units at scales of 1:12000 and 1:24000 on the Lawton and Mount Scott 7.5 minute USGS topographic quadrangles. Measurements were taken of flow banding, flow folding, flow lineation, and columnar jointing. Bedding attitudes were measured from bedded volcaniclastic metasedimentary rocks and along the contact between these rocks and the overlying rhyolite.

A cross-section was constructed perpendicular to strike across a portion of the field area in order to illustrate regional contact relations between the Carlton Rhyolite Group and intrusive granite. A pace-and-compass outcrop map was also drafted for a relatively well-exposed area showing local contact relations between these units. In addition, a measured section was constructed of volcaniclastic metasedimentary rocks separating rhyolite flow units in the study area in order to define vertical facies changes within the volcaniclastic sequence.

Petrographic Analyses

Rock chips that were cut in the rock preparation laboratory at TCU were sent to Spectrum Petrographics in Vancouver, Washington, where 77 thin sections were prepared and stained for alkali feldspar with sodium cobaltinitrite. Detailed petrographic analyses were carried out on those thin sections and variations in rhyolite groundmass textures were examined to document vertical zonations within flows, differences in cooling rate, and emplacement mechanisms, including a search for relict pyroclastic textures. Metamorphic recrystallization and mineralization were also documented, along with relict sedimentary textures within volcaniclastic metasedimentary rocks.
Modal Analyses

Modal analyses were carried out by point counting 17 rock slabs in order to document variability in phenocryst contents. Fifteen of the rock slabs that were point-counted came from a single large flow in the study area, and two of the slabs came from hypabyssal rhyolite intrusions that cut that flow. Samples from a second flow in the Fort Sill area were not point-counted due to the relatively strong metamorphic overprint and the mostly aphanitic texture of that unit.

Phenocrysts are readily apparent on rock slabs, and point counts derived from them are statistically more representative than point counting thin sections due to the larger surface areas of the slabs. The dimensions of each rock slab were roughly similar (~80 cm$^2$), and 500 points per slab were counted at consistent 1-mm intervals between points.

Geochemical Analyses

Twenty-one bulk-rock samples were collected in the field both laterally and vertically throughout the study area for geochemical analyses. Each sample weighed several kilograms and was collected so as to obtain the freshest material. The samples were processed on freshly cleaned equipment in the rock preparation laboratory at TCU. Individual samples were initially crushed using a steel jaw crusher. To minimize contamination the crusher was pre-contaminated by crushing a small part of each sample. That material was discarded and the crusher was cleaned again before processing the main part of the sample. Altered and weathered material was then separated from fresh rock by hand-picking and subsequently discarded. The fresh rock chips were crushed a second time using a smaller ceramic jaw crusher, which was also pre-contaminated between each sample, as described above. Fresh rock was once again separated
from any remaining altered/weathered material. The remaining sample was split into portions weighing ~50 grams by repeated use of the cone-and-quarter technique.

The samples were sent to the GeoAnalytical Laboratory at Washington State University, where they were prepared following standard techniques used in that laboratory. Major elements and some trace elements (Ni, Cr, V, Ga, Cu, Zn, La, Ce, Ba, Th, Nb, Pb, Rb, Sr, Sc, Zr, Y, Nd) were analyzed by X-ray fluorescence (XRF) for all samples. Additional trace element concentrations (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 analyzed for five samples by inductively coupled plasma-source mass spectrometry (ICP-MS). Details of sample preparation, precision, and accuracy for XRF and ICP-MS analyses can be found at: http://soe.wsu.edu/facilities/geolab/technote/.
CHAPTER 2: REGIONAL GEOLOGIC SETTING

Introduction

In response to breakup of the Rodinian supercontinent and opening of the Iapetus Ocean during the Neoproterozoic to early Cambrian, major rift zones developed along the margins of the Laurentian craton and were accompanied by intraplate magmatism (Aleinikoff et al., 1995; Cawood et al., 2001; Tollo et al., 2004; Thomas, 2014a; Yonkee et al., 2014). One of these rift zones, the Southern Oklahoma aulacogen, was associated with voluminous bimodal Cambrian igneous activity that records an impressive magmatic flare-up along the southern Laurentian margin (Fig. 2) (Gilbert, 1983; Hanson et al., 2013; Thomas, 2011, 2014a).

The Southern Oklahoma aulacogen is an elongate structure that trends west-northwest and can be traced ~530 km (based on subsurface and gravity data) from the ancient continental margin in northeast Texas, northwest across southern Oklahoma, and into adjacent parts of the Texas Panhandle (Fig. 2) (Ham et al., 1964; Hanson et al., 2013). However, rifting has been inferred to extend northwest into New Mexico and southern Colorado, suggesting the total length of the rift could be ~1500 km (Larson et al., 1985; Keller and Stephenson, 2007; Keller, 2014). Gravity and magnetic anomalies indicate the width of the rift zone in southern Oklahoma and Texas to be ~65 km and additional geophysical data suggest it is at least 8 to 12 km deep (Keller and Stephenson, 2007; Hanson et al., 2013). The total volume of igneous rocks emplaced within the rift zone in the same area has been estimated by Hanson et al. (2013) to be in excess of 250,000 km$^3$.

Shatski (1946) was the first to recognize the large structural features of southern Oklahoma as an aulacogen, a term he coined for a transverse linear trough extending from an
Figure 2. Regional map of Cambrian rift zones in southeastern North America related to opening of the Iapetus Ocean. Approximate outlines of outcrops of Cambrian igneous rocks in the Wichita and Arbuckle Mountains are indicated. Modified from Hanson et al. (2013); subsurface extent of rhyolite from Ham et al. (1964); early Paleozoic continental margin from Keller and Stephenson, (2007). MVF: Mountain View fault; WVF: Washita Valley fault; BG: Birmingham graben; MVG: Mississippi Valley graben; RCG: Rough Creek graben.
ancient continental margin into the interior of a craton at a high angle. Hoffman et al. (1974) interpreted the Southern Oklahoma aulacogen as the failed arm of a three-armed triple junction that formed during opening of the southern Iapetus Ocean. Alternatively, Thomas (1991, 2011, 2014b) has argued that magmatism related to rifting in southern Oklahoma occurred in a leaky transform-parallel intracratonic fault zone associated with the Iapetan rift system. Because transtension is common in rift zones, the interpretations of Hoffman et al. (1974) and Thomas (1991, 2011, 2014b) may both in part be valid.

The Southern Oklahoma aulacogen appears to have developed along an older Precambrian zone of weakness. A deep Proterozoic basin containing strata ~12 km thick occurs in the subsurface to the south and has been identified on COCORP reflection data (Brewer et al., 1981, 1984; Pratt et al., 1992). This older basin is partly filled with rocks of the Tillman Metasedimentary Group, which are only known from the subsurface (Ham et al., 1964; Gilbert, 1982a; Van Schmus et al., 1993). Ham et al. (1964) considered the Meers Quartzite, which was originally defined by Hoffman (1930) as xenoliths occurring in Cambrian igneous rocks in the Wichita Mountains, to belong to the Tillman Metasedimentary Group. More recently, Gilbert (1982a) interpreted the Meers Quartzite as recording a period of sedimentation during the time span of igneous activity within the aulacogen. This bears directly on the present study, as volcanioclastic rocks separating extrusive units of Carlton Rhyolite in the Fort Sill area may be related to the Meers Quartzite (see Chapters 4 and 5).

The main basement rocks that the Southern Oklahoma aulacogen cuts across consist of the ~1.4 Ga southern midcontinent granite-rhyolite province, which covers extensive areas of the midcontinent in the subsurface and locally crops out in a portion of the Arbuckle Mountains along the northern rift margin. Exposed examples in that area include the Tishomingo and Troy
Granites and the Blue River Gneiss (Ham et al., 1964; Van Schmus et al., 1996; Rohs and Van Schmus, 2007).

Subsequent to Cambrian rifting and magmatism, which is described in more detail below, thermal subsidence of the rift zone ensued and was accompanied by marine transgression. This resulted in the deposition of 4 to 5 km of late Cambrian to Mississippian sedimentary rocks on top of the Cambrian igneous rocks. The upper Cambrian Reagan Sandstone is the oldest transgressive unit that was unconformably deposited on the Cambrian igneous rocks, providing a younger limit on the timing of igneous activity (Ham et al., 1964; Gilbert, 1983). Inversion of the Southern Oklahoma aulacogen occurred during the Pennsylvanian to Early Permian. Throughout this time, major Cambrian rift faults were reactivated in a compressional to transpressional regime related to collisional Ouachita orogenesis to the southeast, or to more distant far-field stresses transmitted inland from the Cordilleran margin to the west (Granath, 1989; Perry, 1989; Ye et al., 1996). This period of deformation resulted in the structural elements that define southern Oklahoma as the most intensely deformed region in the Paleozoic cratonic interior of the United States (Denison, 1982). Large fault-bounded blocks form a series of uplifts, exposing portions of the Cambrian magmatic assemblage, and linked basins. These fault blocks define the Amarillo-Wichita-Criner-Arbuckle structural axis. Trending at N60° to 70°W across the southern midcontinent, they also define the present trend of the Southern Oklahoma aulacogen. Major uplifted blocks include the Wichita and Arbuckle Mountains, which are flanked by deep Paleozoic basins that include the Anadarko basin (one of the deepest basins in North America), and the Hardeman-Hollis, Marietta, and Ardmore basins (Ham et al., 1964; Gilbert, 1983; McConnell and Gilbert, 1990).
Following Pennsylvanian to Early Permian uplift, the midcontinent remained relatively stable during the Mesozoic and Cenozoic. During this period of quiescence, Cambrian igneous rocks of southern Oklahoma were buried in their own detritus (e.g., Permian Post Oak Formation) and in sediments derived from the Ouachita Mountains (Chase, 1954; Al-Shaieb et al., 1980; Gilbert, 1983). Consequently, the rift assemblage has been well preserved and only recent uplift and erosion have partly exposed the igneous floor of the rift zone, making it one of the best-preserved and best-exposed examples of igneous activity associated with ancient intracontinental rifting in North America (McConnell and Gilbert, 1990).

**Wichita Igneous Province**

The pioneering work of Ham et al. (1964) provided the first extensive study of igneous rocks related to rifting in southern Oklahoma. They established a formal lithostratigraphic framework and nomenclature for the principal rock units, grouping them together as the Wichita province. At the time, Ham et al. (1964) included the Tillman Metasedimentary Group as part of the Wichita province, interpreting those rocks as recording initiation of basin formation tectonically linked to magmatism within the Southern Oklahoma aulacogen. As noted above, more recent work suggests the Tillman Metasedimentary Group represents a period of Proterozoic sedimentation that is unrelated to Cambrian igneous activity (Brewer et al., 1981; Van Schmus et al., 1993). In order to avoid confusion, the term Wichita igneous province will be used in this thesis to refer specifically to igneous rocks emplaced during development of the Southern Oklahoma aulacogen, following Hanson and Eschberger (2014).

The Wichita igneous province is a bimodal assemblage that includes mafic rocks of the Raggedy Mountain Gabbro Group (subdivided into the Glen Mountains Layered Complex and Roosevelt Gabbro Group), the Navajo Mountain Basalt-Spilite Group (known only from the
subsurface), and younger felsic rocks assigned to the Carlton Rhyolite and Wichita Granite Groups. A suite of late diabase dikes cuts all other igneous rocks in the province and rare rhyolite dikes cut some of the younger felsic units (Ham et al., 1964). Figure 3 is a schematic diagram illustrating the cross-sectional relationships of igneous rocks exposed in the Wichita igneous province.

**Mafic Rocks**

The Raggedy Mountain Gabbro Group was a term first introduced by Ham et al. (1964) to describe all gabbroic rocks in the Wichita igneous province. Later, Powell et al. (1980) recognized that the group consists of two distinct units and recommended it be subdivided into the Glen Mountains Layered Complex and the Roosevelt Gabbro Group. This terminology has been followed in subsequent literature.

**Glen Mountains Layered Complex**

The initial phase of igneous activity within the Southern Oklahoma aulacogen is thought to have begun with emplacement of the Glen Mountains Layered Complex, which forms the substrate of the rift zone and is the oldest igneous rock unit exposed in the Wichita Mountains (Fig. 3) (Gilbert, 1983). Outcrops of the complex occupy an area of ~2,500 km² in the Wichita Mountains, with an estimated vertical thickness up to 1.1 km (Lambert et al., 1988). Based on subsurface well data the complex has an inferred total areal extent >15,500 km² and is >2.4 km thick (Ham et al., 1964). Described as a lopolith, it is composed mainly of layered anorthositic gabbro and troctolite. Major cumulus phases include plagioclase and olivine. Orthopyroxene, clinopyroxene, magnetite, and ilmenite occur as intercumulus phases (Powell and Phelps, 1977; Powell, 1986; Lambert et al., 1988). The tholeiitic character and distinctive layering of this
Figure 3. Schematic cross-section of igneous rocks exposed in the Wichita Mountains. Modified from Hogan and Gilbert (1998).
enormous body make it very similar to other layered mafic intrusions, such as the Bushveld, Stillwater, and Duluth Complexes (Powell and Phelps, 1977; McConnell and Gilbert, 1990).

Based on phase chemistry, textures, and general mineral assemblages, Powell and Phelps (1977) argued that the exposed section of the Glen Mountains Layered Complex approximates the midsection of a typical layered mafic complex, possibly analogous to the main zone A of the Bushveld and the anorthosite zone of the Stillwater Complex. This requires a substantial amount of erosion prior to later igneous activity. It has been postulated that some 2 to 4 km of the upper Glen Mountains Layered Complex and an unknown amount of overburden were removed by erosion preceding emplacement of additional mafic magmas (Roosevelt gabbros) and voluminous felsic magmas (Carlton Rhyolite and Wichita Granite Groups). In addition, angular discordance between layering in the Glen Mountains Layered Complex and later units implies that rotation of the Glen Mountains Layered Complex occurred during ongoing Cambrian tectonism (Powell and Phelps, 1977; Gilbert, 1983; McConnell and Gilbert, 1990). Lambert et al. (1988) obtained an Rb-Sr isochron age of 577 ± 165 Ma from four whole-rocks samples and a three-point mineral-whole-rock Sm-Nd isochron age of 528 ± 29 Ma for the complex.

**Roosevelt Gabbro Group**

Following tilting and erosion of the layered complex, the tholeiitic Roosevelt gabbros were emplaced, forming several small, steep-sided plutons that intrude the layered complex (Hogan et al., 1998). The gabbros contain primary hydrous minerals (biotite and amphibole) and are compositionally unrelated to the layered complex (Powell et al., 1980; Powell, 1986). Internal layering is also pronounced in the Roosevelt gabbros, but is discordant to layering in the Glen Mountains Layered Complex (Powell, 1986). The Mount Sheridan Gabbro is the largest of the Roosevelt gabbros and has an exposed areal extent of ~24 km². A recently obtained U-Pb
titanite crystallization age of 577 ± 2 for that pluton indicates intrusion of the Roosevelt gabbros well before emplacement of distinctly younger felsic rocks (Hogan and Amato, 2015). Previously, the Mount Sheridan Gabbro yielded $^{40}\text{Ar}^{39}\text{Ar}$ ages of 533 ± 4 and 533 ± 2 Ma on biotite and hornblende, respectively (Hames et al., 1998). Hogan and Amato (2015) argue that intrusion of younger granite caused thermal resetting of the K-Ar isotopic system within the gabbro. However, field evidence indicates that intrusion of some of the Roosevelt gabbros may have postdated granite emplacement (Gilbert and Hogan, 2010). This is also supported by a magnetic survey conducted by Price et al. (1998a) on the Sandy Creek Gabbro, a member of the Roosevelt gabbros, which suggests that the Sandy Creek Gabbro intrudes the Mount Scott Granite.

**Navajo Mountain Basalt-Spilite Group**

The Navajo Mountain Basalt-Spilite Group is known only from the subsurface and was originally described by Ham et al. (1964) using drill cuttings from eleven basement wells in the western part of the province near the Wichita Mountains. The thickest penetration of the group was 320 m and the base was not reached. The assemblage is comprised mostly of variably altered basaltic to intermediate lavas. However, palagonite tuffs occur in the lower ~50 m of one well, indicating that explosive phreatomagmatic eruptions took place in at least some parts of the developing volcanic field as uprising magma came in contact with external water in either subaqueous or terrestrial settings. In this part of the province, Ham et al. (1964) interpreted the Navajo Mountain Basalt Spilite-Group to be unconformably overlain by the younger Carlton Rhyolite. Gilbert (1983) considered the basalts to be the eruptive equivalent of the Glen Mountains Layered Complex.
More recently, subsurface data farther to the southeast, in the Arbuckle Mountains area, indicate that large amounts of basaltic to intermediate volcanic rocks both underlie and are intercalated with rhyolites (Puckett, 2011; Bulen, 2012; Hanson et al., 2013; Brueseke et al., 2014; Puckett et al., 2014; Hobbs, 2015). These data suggest that basaltic volcanism was much more widespread throughout the rift zone than previously recognized and overlapped in time with rhyolitic volcanism. Geochemical data indicate that mafic to intermediate volcanic rocks in the Wichita igneous province have ocean-island-basalt-like, tholeiitic to slightly alkaline compositions, making them similar to flood basalts documented in other large igneous provinces (Bulen, 2012; Hanson et al., 2013; Brueseke et al., 2014; Hobbs, 2015). Isotopic ages have not been obtained for any of the basalts in the Wichita igneous province.

Felsic Rocks

Carlton Rhyolite Group

Ham et al. (1964) were the first to show that the two outcrop areas of Cambrian rhyolite in the Wichita and Arbuckle Mountains, separated by ~130 km, are connected by a seemingly continuous sequence of rhyolites in the subsurface. They introduced the term Carlton Rhyolite Group to denote all Cambrian rhyolitic volcanic rocks in southern Oklahoma. The Carlton Rhyolite covers an estimated area of ~40,000 km² in the subsurface (Fig. 2) and is the stratigraphically highest major igneous unit in the Southern Oklahoma aulacogen (Ham et al., 1964). In the subsurface of the Wichita Mountains area the rhyolites are underlain by the Navajo Mountain Basalt-Spilite Group, while in exposed parts of the same area they appear to have to been extruded directly onto the erosional unconformity atop the Glen Mountains Layered Complex (Ham et al., 1964; Gilbert, 1983).
Regional stratigraphic relations suggest that rhyolite exposures in the Arbuckle Mountains and in the Slick Hills in the Wichita Mountains represent higher parts of the volcanic sequence because the upper Cambrian Reagan Sandstone overlies the rhyolites in those areas. The Fort Sill section in the Wichita Mountains is thought to represent lower parts of the volcanic sequence based on contact relations with intrusive granites (Ham et al., 1964; Hanson, 1977; Gilbert, 1982a; Hanson et al., 2014). Hanson et al. (2009) reported U-Pb zircon dates of ~532 Ma for two flows at the top and base of the rhyolite sequence exposed in the Bally Mountain area in the Slick Hills. Thomas et al. (2012) obtained U-Pb zircon dates of 539 ± 5 Ma from a hypabyssal felsic intrusion cutting Carlton Rhyolite in the Timbered Hills in the western Arbuckle Mountains, and 536 ± 5 Ma from a rhyolite dike intruding Mesoproterozoic basement in the eastern Arbuckle Mountains. A U-Pb zircon age of 534 ± 5 Ma for rhyolite in the Fort Sill area was reported by Hogan and Amato (2015).

Recent work on outcrops of the Carlton Rhyolite (see Chapter 1 for description of outcrop locations) has documented at least 31 individual flow units in the Wichita Mountains and nine additional flows exposed in the Timbered Hills in the Arbuckle Mountains (Eschberger, 2012; Eschberger et al., 2014; Hanson et al., 2014; Boro, 2015). In addition, many more rhyolite flows exist in the subsurface (e.g., Puckett et al., 2014). Single exposed rhyolite flows, where the tops and bases can be positively identified, range in thickness from ~80 to ~370 m. Thicker flows exist, although the top and/or base cannot be determined with certainty. One such flow in the East Timbered Hills is 600 m thick but the top is erosional (Eschberger et al., 2014). This is the thickest flow so far documented in the Carlton Rhyolite. Work in the Bally Mountain area in the Slick Hills has documented a sequence ≥2 km thick that comprises nine individual rhyolite flow units, making it the thickest exposed stratigraphic succession of Carlton Rhyolite known to
date (Hanson et al., 2014). Although most flows can only be traced a few kilometers in outcrop before going under cover or being truncated by intrusive contacts or faults, their preserved morphologies suggest they originally formed broad tabular sheets.

Lavas of the Carlton Rhyolite Group are typically porphyritic, with phenocrysts of alkali feldspar, quartz, oxides, minor plagioclase, and pseudomorphs of mafic silicates, presumably mostly pyroxene and/or fayalite. Quartz phenocrysts are absent in many flows. Accessory minerals include zircon and apatite. The groundmass displays a variety of textures, including flow banding and flow lamination, spherulites, lithophysae, snowflake texture, felsitic texture, and relict perlitic cracks. These textures define a distinctive vertical zonation reflecting gradients in cooling rates in many of the rhyolite flows. In general, upper and lower margins of flows display well-developed flow banding together with relict perlitic texture, indicating the original presence of glass. Zones rich in lithophysae occur within the inner parts of the glassy margins in many cases. Flow breccia and peperite have been described at the base of some flows. Flow interiors are defined by massive, homogenous felsitic rhyolite with extensive development of randomly oriented tridymite needles in the groundmass (now inverted to quartz). Generally, the needles increase in size towards the middle of flows, indicating slow, uniform cooling of the interior after the lava ceased flowing (Hanson et al., 2013, 2014; Eschberger et al., 2014).

The regular internal cooling zonation and inferred broad tabular shape of Carlton Rhyolite flows are inconsistent with emplacement as short, thick lava flows or domes. Instead, the available outcrops most likely represent erosional remnants of laterally extensive sheet-like flows similar to those described in other intraplate, A-type felsic volcanic provinces (e.g., Henry et al., 1988; Henry and Wolff, 1992; Branneney et al., 2008). In this regard, it is interesting to note that tridymite needles (now inverted to quartz) in the groundmass with textures resembling those
in the Carlton Rhyolite have been described in extensive, A-type felsic units in South Africa (Twist and French, 1983) and Australia (Trendall, 1995).

Major eruptive centers for Carlton Rhyolite flows have not been identified. Gravity data have confirmed the absence of caldera structures within the Southern Oklahoma aulacogen. It has been assumed that the rhyolites were erupted along linear fissures with normal faults providing pathways for magma movement during rifting (Gilbert, 1983; McConnell and Gilbert, 1990). Presumably the fissures are now buried under the thick rhyolitic pile. This model is consistent with known or inferred eruptive centers in some other large felsic intraplate volcanic fields (e.g., Bonnichsen and Kaufman, 1987; Henry et al., 1988, 1990; Milner et al., 1992; Manley, 1995, 1996a, 1996b). It is also supported by recent work by Hanson et al. (2014), who described a feeder dike to one of the flows exposed on Bally Mountain. Neither the flow nor the dike contains pyroclastic textures, indicating that at least that particular flow erupted as lava directly from the vent.

**Wichita Granite Group**

Members of the Wichita Granite Group were intruded partly along the base of the rhyolitic volcanic sequence, forming a series of sheet-like bodies that spread out along the unconformity on older mafic rocks (Fig. 3). In places in the subsurface, granite sills also intrude volcanic rocks within the sequence (Puckett et al., 2014). The granites and rhyolites are thought to have been emplaced penecontemporaneously, with the growing volcanic pile acting as a crustal magma trap impeding the further rise of felsic liquids (Hogan and Gilbert, 1995, 1997; Hogan et al., 1998, 2000).

Initially, rising felsic magma batches ponding along this crustal magma trap crystallized rapidly as fine-grained granophyric granite sheets at relatively low pressures. Typical examples
of fine-grained granite sheets exposed in the Wichita Mountains include the Mount Scott, Cache, and Headquarters Granites. These fine-grained granites are abundant throughout the Wichita Mountains, with the Mount Scott Granite being the largest recognized individual sheet. It is at least 55 km long and 17 km wide, and has a thickness of ~ 0.5 km (Hogan and Gilbert, 1997; Hogan et al., 2000; Price, 2014a).

As a result of the addition of more material to the volcanic-plutonic pile, the crustal magma trap was displaced deeper in the crust. Subsequent intrusions of granite formed less abundant coarse-grained granite sheets, which crystallized at somewhat higher pressures. Coarse-grained granite sheets in the Wichita Mountains are represented by the Quanah and Reformatory Granites (Hogan and Gilbert, 1997; Hogan et al., 2000).

In general, members of the Wichita Granite Group are metaluminous alkali feldspar leucogranites. Hypersolvus granites predominate, although subsolvus granites are locally present. Porphyritic texture is common. Typical minor phases include amphibole, biotite, and Fe-Ti oxides. Sodic amphiboles and pyroxenes occur in the Quanah Granite and locally in other coarse-grained granite sheets. Accessory minerals include zircon, titanite, apatite, fluorite, and in some cases, allanite (Myers et al., 1981; Gilbert and Myers, 1986; Hogan et al., 2000).

Several workers have reported isotopic age dates for the Wichita Granite Group. Wright et al. (1996) and Degeller et al. (1996) reported U-Pb zircon dates ranging from 535 ± 3 Ma to 530 ± 1 Ma for some of the granites. Most recently, Hogan and Amato (2015) obtained a U-Pb zircon age of 538 ± 6 Ma for the Mount Scott Granite. They also reported a U-Pb zircon age of 535 ± 2 Ma for a granite pegmatite dike that cuts the Mount Sheridan Gabbro of the Roosevelt Gabbro Group.
**Chemistry and Petrogenesis of the Felsic Rocks**

The Wichita Granite and Carlton Rhyolite Groups are inferred to be comagmatic and are classic examples of felsic magmas emplaced in a crustal rifting environment. Both groups show characteristic A-type chemical features, such as low CaO, high Fe/Mg ratios, elevated abundances of high-field-strength elements, and within-plate trace-element patterns (Myers et al., 1981; Gilbert and Myers, 1986; Weaver and Gilbert, 1986; Hanson et al., 2013; Hanson and Eschberger, 2014).

The unusual sheet-like geometry of the Wichita granites and the inferred extensive nature of at least some Carlton Rhyolite flows have been attributed to fluid behavior of high-temperature, fluorine-rich magmas with low H$_2$O contents (Hogan and Gilbert, 1997; Price et al., 1999); Zr geothermometry by Hogan and Gilbert (1997) indicates possible magmatic temperatures of ~ 950° C for the granites and rhyolites. A-type magmas of the Wichita igneous province would have had much lower viscosities than more typical felsic liquids, allowing them to be intruded as low-aspect-ratio sheet granites and erupted nonexplosively to form laterally extensive rhyolite lavas (Hogan and Gilbert, 1995, 1997; Hogan et al., 1998, 2000; Hanson and Eschberger, 2014).

The Wichita Granite and Carlton Rhyolite Groups were originally thought to be derived by partial melting of Precambrian basement rocks from mafic intraplateing associated with the rifting event (Gilbert and Myers, 1986; McConnell and Gilbert, 1990). However, recent trace element and Nd and Sr isotopic data for both the granites and rhyolites are inconsistent with those expected for magmas generated entirely from partial melting of older basement rocks. Trace-element patterns indicate derivation of many of the felsic magmas from a mafic source compositionally similar to ocean-island basalt. The limited isotopic data suggest the felsic rocks
are partly the products of either fractional crystallization of basaltic parental magmas or partial melting of a mafic underplate (Hogan et al., 1995). Crustal assimilation still must have played a role in modifying the compositions of many of the felsic magmas, as has been shown by trace-element data available for a much larger suite of felsic rocks than the existing isotopic data (Hanson and Eschberger, 2014).

**Diabase and Rhyolite Intrusions**

Diabase dikes, sheets and sills are relatively abundant throughout the Southern Oklahoma aulacogen and are known to cut all other major igneous units. Reliable isotopic age dates have not been obtained for the diabase intrusions. They do not cut the Reagan Sandstone, which unconformably overlies the Carlton Rhyolite. Their orientations vary, but in general they follow the northwest structural trend of the rift axis (Denison, 1995).

In the eastern Arbuckle Mountains, northeast of the northern margin of the rift zone, diabase dikes intrude exposed Mesoproterozoic basement rocks. The dikes have olivine- to quartz-normative tholeiitic compositions and are described by Lidiak et al. (2014) as the Mill Creek diabase dike swarm. Although some of the dikes are considered to be Proterozoic in age, most are thought to have been emplaced during Cambrian rifting (Denison, 1995). Field evidence indicates that the dikes increase in abundance near the northern margin of the rift zone. They are typically less common in outcrops of Carlton Rhyolite within the rift zone, however, suggesting that most of the Mill Creek dike swarm records a pulse of rift-related magmatism that preceded emplacement of Wichita felsic rocks (Denison, 1995; Lidiak et al., 2014).

A suite of late diabase and rhyolite dikes represents final igneous activity within the Southern Oklahoma aulacogen. A few of the rhyolite dikes in the Wichita Mountains cut the Mount Scott Granite, and it has been suggested that some of the rhyolite overburden covering the
granite, and possibly some of the granite as well, were removed by erosion prior to emplacement of the dikes, causing them to cool rapidly at shallow levels (Gilbert and Powell, 1988; Gilbert and Denison, 1993). Hogan and Amato (2015) obtained a U-Pb zircon age of 536 ± 6 Ma from a rhyolite dike cutting granite exposed near Medicine Park in the Wichita Mountains. Hypabyssal felsic intrusions are relatively common in the Arbuckle Mountains, where Eschberger (2014) and Toews (2015) have mapped many examples in the East and West Timbered Hills, respectively. In general, they occur as plug-like intrusions of rhyolite or microgranite that cut Carlton Rhyolite. As noted previously, Thomas et al. (2012) reported a U-Pb zircon age of 539 ± 5 Ma for one of the rhyolite intrusions in the East Timbered Hills.

Overall, the late diabases range from tholeiitic to transitional or alkaline and have within-plate trace-element characteristics (DeGroat et al., 1995; Eschberger et al., 2014; Toews, 2015). DeGroat et al. (1995) showed diabase intrusions in the Wichita Mountains to be geochemically indistinguishable from the Roosevelt gabbros, while Hogan et al. (1995) showed the late diabase dikes to be derived from isotopically similar sources to the felsic samples they analyzed.

The rhyolite and late diabase dikes indicate that rift-related faults and fractures likely acted as conduits for the transport of both mafic and felsic magmas to higher crustal levels throughout the duration of rift development. The late diabase dikes also indicate that mafic magmas were present throughout the magmatic history of the Wichita igneous province.
CHAPTER 3: GEOLOGIC SETTING OF THE STUDY AREA

Introduction

The Fort Sill area contains the most extensive exposures of the Carlton Rhyolite Group anywhere in the Wichita Mountains (Fig. 1). Two rhyolite flows are present in the Fort Sill area, the Davidson metarhyolite and the stratigraphically higher Fort Sill rhyolite (Plate I and Fig. 4). They are separated by a discontinuous unit of clastic metasedimentary rocks deposited on an irregular erosional surface cut into the Davidson metarhyolite (Fig. 5). The U-Pb zircon age of 534 ± 5 Ma obtained by Hogan and Amato (2015) for rhyolite in the Fort Sill area comes from that unit.

The Mount Scott Granite intrudes both flows. Its extent shown in Plate I and Figure 4 also includes the smaller Rush Lake and Medicine Park Granites, which were mapped in the study area by Price (1998, 2014a) and are considered by him to be related to the Mount Scott Granite. The Quanah and Cache Granites intrude the Fort Sill rhyolite in the southwest part of the area (Plate I and Fig. 4). Conglomerate, sandstone, siltstone, and shale of the Permian Post Oak and Garber-Hennessey Formations cover large parts of the study area, and Quaternary alluvium occurs in drainage channels and on modern flood plains (Plate I and Fig. 4) (Havens, 1977; Stanley and Miller, 2005).

My work in the Fort Sill area builds on previous studies by Schoonover (1948), Gilbert (1982a, 1982b, 1986), Sides and Miller (1982), Miller et al. (1982), and Price (1998, 2014b). In names for formal lithodemic units used herein all the words are capitalized. For informally named rock units the lithologic term is lower case (e.g., “Pratt Hill quartzite”).
Figure 4. Geologic map of the Fort Sill area. Location shown in Figure 1. Rush Lake and Medicine Park Granites of Price (2014a) are included with Mount Scott Granite. Map includes data from Schoonover (1948), Gilbert (1962, 1966), Miller et al. (1982), Gilbert and Powell (1988), and Price (1998). Location of cross-section A-A' shown in Figure 6 and area shown in Figure 7 are indicated.
Figure 5. Schematic diagram of an idealized section through the Carlton Rhyolite Group in the Fort Sill area (not to scale). FSr = Fort Sill rhyolite; Dmr = Davidson metarhyolite; PHq = Pratt Hill quartzite.

- Eroded top
- Upper margin with local pockets of flow breccia (fb), flow folds, and continuous, partly originally glassy flow bands.
- Massive felsitic center with crude hexagonal columns. Discontinuous flow banding with spherulitic texture visible in many areas.
- Chilled lower margin with relict perlitic texture and thin, well-developed flow lamination.
- Localized basal peperite (thickness exaggerated).
- Discontinuous interval of clastic meta-sedimentary rocks; includes Pratt Hill quartzite.
- Lower flow (Davidson metarhyolite) with delicate flow lamination, complex flow folds, and local flow breccia (fb).
In the general area of Fort Sill, major geologic contacts have shallow dips of 10 to 15° to the south to southeast (Fig. 6), including the gabbro-granite contact on the north flank of Mount Scott (Gilbert and Hogan, 2010) and the contact between the Fort Sill rhyolite and the underlying Pratt Hill quartzite and laterally equivalent volcanoclastic rocks (Sides and Miller, 1982, and this study). Sedimentary strata in the upper Cambrian to Ordovician Timbered Hills and Arbuckle Groups exposed in several small hills south of the study area typically dip 14 to 20° to the southeast or southwest (Chase et al., 1956), although these rocks are partly disturbed by faults (Chase et al., 1956; Ham et al., 1964). The Mount Scott Granite is inferred to form a sill beneath the Carlton Rhyolite Group in the study area (Fig. 6), similar to other granites in the Wichita Mountains and in parts of the subsurface in the Southern Oklahoma aulacogen (Ham et al., 1964). This interpretation is consistent with regional field relations (Hogan and Gilbert, 1995; Hogan et al., 1998; Hogan et al., 2000; Price, 2014a), but differs from the interpretation of Gilbert (1982b) concerning the relations in the area south of Mount Scott (discussed below).

**Intrusive Igneous Contacts**

Many currently recognized intrusive igneous contacts in the Wichita Mountains were depicted as faults on the first state geologic map of Oklahoma by Miser (1954), an interpretation later followed by Chase et al. (1956) and Havens (1977). Several factors played a role in the interpretation of faults on those maps, including prominent lineaments visible on aerial photographs and topographic maps and, in places, the exceptionally straight nature of the gabbro-granite contact that is commonly parallel to the lineaments. Gilbert (1984) argued that many of the faults drawn near geologic contacts on the earlier maps could instead be interpreted as intrusive igneous contacts. His work mainly focused on the gabbro-granite contact exposed in the central lowland of the eastern Wichita Mountains, west of the present study area.
Figure 6. Cross-section A-A’ across part of the Fort Sill area. Location is shown on Plate I and Figure 4. Displacement on the Little Medicine Creek and Deer Creek Canyon Fault Zones and dip of units south of Pratt Hill is uncertain. Vertical exaggeration is 2:1.
In the present study area, intrusive igneous contacts between units of the Carlton Rhyolite Group and the Mount Scott and Quanah Granites are typically obscured or ambiguous in nature. They are commonly buried by Permian sediments of the Post Oak Formation and/or thin soil and alluvium or are covered by vegetation or water (e.g., Lake Elmer Thomas). Nevertheless, several key locations either exhibit well-defined contact relations or the relations between units can be reasonably inferred.

Along an unnamed ridge west of Lake Elmer Thomas on the Fort Sill Military Reservation, Mount Scott Granite intrudes the base of the Fort Sill rhyolite along a relatively straight contact trending east to west. At locality A (Fig. 7), complex, interfingering relations occur between Fort Sill rhyolite and the granite, and the contact is defined by a zone ~15 m wide with dike-like fingers of granite as much as 1 m wide injected into rhyolite. Thermal metamorphism has imparted a granoblastic texture to the groundmass of the Fort Sill rhyolite, and the granite shows a fine-grained chilled margin, particularly within fingers intruded into rhyolite. The granite coarsens away from the contact and contains distinct ovoid alkali feldspar phenocrysts 2 to 3 mm long typical of the main part of the Mount Scott Granite (Price, 2014a).

Near a small drainage to the east of this location, Mount Scott Granite intruded along the base of part of the rhyolitic volcaniclastic metasedimentary sequence between the Davidson metarhyolite and overlying Fort Sill rhyolite (locality B, Figs. 7 and 8). There, the volcaniclastic rocks have also been thermally metamorphosed and the granite displays a chilled, fine-grained margin. The contact can be traced for several meters before becoming covered. The base of the Fort Sill rhyolite at this locality is obscured by grass and thin soil, although the outcrop configuration suggests an interfingering relationship similar to that described previously.
Figure 7. Geologic map of part of the Fort Sill area showing localities A-G discussed in text. See Figure 4 for location and legend.
Figure 8. Outcrop map showing rhyolitic volcaniclastic metasedimentary interbed at the base of the Fort Sill rhyolite (locality B, Fig. 7). Mount Scott Granite has intruded along the base of the metasedimentary rocks.
Above the grass-covered base, the Fort Sill rhyolite shows a relatively coarse, sugary groundmass in hand sample that is suggestive of thermally induced granoblastic recrystallization of the quartzo-feldspathic groundmass.

Elsewhere in the mapped area (Plate I and Fig. 4), except where covered by Permian and Quaternary sediments, the Davidson metarhyolite is truncated discordantly by Mount Scott Granite. This relationship is best exposed in the Hide-A-Way area in Fort Sill (locality C, Figs. 7 and 9), where the contact is irregular. Blocks of Davidson metarhyolite as much as 50 m across are partly entrained within granite, suggesting an interfingering relationship, and some blocks as much as 5 m across are fully encased within the granite. The granite along the contact shows the same type of chilled margin as described above.

Gilbert (1982b) argued that in the area between Mount Scott and the southern end of Lake Elmer Thomas, the Mount Scott Granite transgressed over the Fort Sill rhyolite. This interpretation conflicts with observations given above. Also, as discussed below, the contact metamorphic overprint in the Fort Sill rhyolite shows a marked decrease upward in the unit, which is inconsistent with the interpretation of Gilbert (1982b). I infer that outcrops of Davidson metarhyolite at the southern foot of Mount Scott represent a large xenolith or septum contained within the interior of the Mount Scott Granite sill (Fig. 6).

**Faults**

Two unnamed main faults in the study area were previously mapped by Havens (1977), although I suspect they were inferred based on lineaments visible on aerial photographs and topographic maps (Plate I and Fig. 4). In the Wichita Mountains Wildlife Refuge southwest of Mount Scott, the structurally complex Little Medicine Creek Fault Zone (my new term) can be traced ~3 km from the headwater canyon of Little Medicine Creek eastward along the creek to
Figure 9. Sharp, intrusive contact between Davidson metarhyolite (left of hammer) and Mount Scott Granite (right of hammer) at locality C (Fig. 7).
the vicinity of the Mount Scott Picnic Area. Along the trace of the fault, cataclastically sheared and brecciated rhyolite (Fig. 10A) is, in places, juxtaposed against Mount Scott Granite showing similar shearing and brecciation. Gilbert and Powell (1988) previously noted this brittle deformation in the vicinity of Quetone Overlook. Brittle deformation related to the fault occurs in a zone ≤0.5 km wide, which disappears under cover towards the east and west. Along the westernmost exposed part of the fault zone, south of Quetone Overlook (locality D, Fig. 7), a wedge-shaped outcrop of highly oxidized and fractured Fort Sill rhyolite extends up the north flank of the canyon cut by Little Medicine Creek and narrows westward. Pervasively fractured Mount Scott Granite surrounds this mass of Fort Sill rhyolite and is unconformably overlain by conglomerate of the Post Oak Formation. Along the creek bed towards the east, pseudotachylite occurs as veins ≤1 cm wide filling cracks between brecciated fragments of Fort Sill rhyolite (Fig. 10B). The presence of pseudotachylite is indicative of intense heat generated during frictional sliding along the fault plane (van der Pluijm and Marshak, 1997).

To the south, in Deer Creek Canyon, a second fault zone ~75 m wide cuts the Fort Sill rhyolite (Plate I and Figs. 4 and 7). This fault zone, which I term the Deer Creek Canyon Fault Zone, is defined by an east-west-trending linear zone of cataclastically sheared and brecciated rhyolite that can be traced for ~6.3 km before disappearing under cover. The deformation style is entirely brittle and rapidly dissipates on either side of the fault zone. Exposures of Fort Sill rhyolite on opposite sides of the fault appear to represent the homogenous interior of the flow (see Chapter 6), possibly suggesting minimal vertical offset along the fault.

The amount of offset and sense of motion are undetermined along both faults. Neither fault extends into the Permian Post Oak Formation to the west, suggesting deformation occurred during Cambrian rifting or Pennsylvanian inversion of the Southern Oklahoma aulacogen.
Figure 10. (A) Strongly fractured and cataclastically sheared Fort Sill rhyolite in Little Medicine Creek Fault Zone at locality D in Figure 7. (B) Pseudotachylite filling fractures in the Fort Sill rhyolite farther east in the fault zone.
Rhyolite Intrusions

Two previously unrecognized small hypabyssal rhyolite intrusions with distinctly different groundmass textures from the Fort Sill rhyolite penetrate that unit (Plate I and Fig. 4). As shown in Chapter 7, the intrusions also have different geochemical compositions from either the Davidson metarhyolite or the Fort Sill rhyolite. At first glance outcrops of the rhyolite intrusions do not appear significantly different from typical Fort Sill rhyolite, and it is likely that such intrusions are more abundant in the area than currently recognized.

One intrusion is exposed on the lower part of the southwest slope of Carlton Mountain (locality FS-125, Plate I and Fig. 4), and the other crops out near the summit of Thompson Hill (locality FS-130, Plate I and Figs. 4 and 7). The intrusions form isolated exposures with rounded outcrops that protrude above the grass-covered hills. They are mineralogically similar to the Fort Sill rhyolite and contain 2.6 to 4.2% quartz and 15.0 to 18.2% alkali feldspar phenocrysts (see Table 1 in Chapter 6). Accessory zircon ≤0.08 mm in length is also present. The intrusions have distinctly coarser groundmass textures than the Fort Sill rhyolite. Randomly oriented tridymite needles (now inverted to quartz) ≤1 mm long are abundant in the groundmass (Fig. 11A) and occur with interstitial microgranophyre (Fig. 11B). Also, unlike the Fort Sill rhyolite, the intrusions contain rare, rounded basaltic inclusions (Fig. 12A), which may record mingling of mafic and felsic magmas in the parent magma chamber. The inclusions are generally ≤3.5 cm across and typically weather out, leaving oval-shaped pits (Fig. 12B).

Two rhyolite dikes cut Mount Scott Granite in the study area (Plate I and Figs. 4 and 7). One of these dikes was mapped by Gilbert (1982b) at the southern base of Mount Scott. A more thoroughly documented rhyolite dike is exposed in a roadcut on Highway 49 directly north of the James A. Manning State Fish Hatchery (locality E, Fig. 7), and is the dike mentioned in Chapter...
Figure 11. (A) Photomicrograph (plane light) of rhyolite intrusion on Carlton Mountain (sample FS-125) showing coarse, randomly oriented clear tridymite needles (inverted to quartz). Width of view is ~2.5 mm. (B) Photomicrograph (crossed polars) of a different part of the same sample showing microgranophytic texture in the groundmass (red arrows). Width of view is ~2.5 mm.
Figure 12. (A) Rounded mafic inclusion within rhyolite intrusion exposed on Thompson Hill (near locality FS-130, Plate I and Figs. 4 and 7). (B) Outcrop of rhyolite intrusion exposed on Carlton Mountain (near locality FS-125, Plate I and Fig. 4) showing oval-shaped pits caused by weathering of mafic inclusions.
2 from which Hogan and Amato (2015) obtained a U-Pb zircon age of 536 ± 6 Ma. Ham et al. (1964) first documented this dike and considered it to demonstrate that Wichita granites and Carlton Rhyolite were broadly contemporaneous. Later, Gilbert and Powell (1988) recognized the tectonic significance of the dike and concluded that a substantial amount of overburden was removed prior to emplacement of the dike, which must have been intruded late in the igneous history of the Southern Oklahoma aulacogen after some amount of uplift. More recently, O’Donnell (2008) carried out a detailed study of the rhyolite dike and concluded that it was intruded at a depth of ~2 km.

**Diabase Dikes**

Diabase intrusions in the Fort Sill area generally form small dikes. A number of these dikes cutting felsic units in the area have been reported by earlier workers (Schoonover, 1948; Gilbert, 1982b, 1986; Gilbert and Powell, 1988; Miller et al., 1982; Price, 1998).

In addition to those already reported, I have mapped three previously undocumented diabase dikes cutting the Fort Sill rhyolite (Plate I and Figs. 4 and 7). The presence of one of these dikes, located on the east side of Jones Ridge (northeast of locality FS-137, Plate I and Figs. 4 and 7), was only detected by the abrupt appearance of abundant, dark-colored diabase float standing out in stark contrast against the weathered, reddish Fort Sill rhyolite; in situ outcrops of the dike could not be located. A second diabase dike was mapped within a north-trending drainage northwest of the summit in the same general area (north of locality FS-137, Plate I and Figs. 4 and 7). That dike trends N50°W and is ~4 m wide. It shows well-exposed contacts with the Fort Sill rhyolite, which has dark-gray baked zones adjacent to the dike. The length of the dike is unknown because it crops out only within the narrow drainage. A third diabase dike was mapped at the base of Heyls Hill along the east bank of Medicine Creek (near
locality FS-88, Plate I and Fig. 4). Due to poor exposure, the trend and dimensions of the dike could not be determined. In thin section, the dike exhibits subophitic texture defined by euhedral to subhedral plagioclase laths ≤0.7 mm long partially enclosed by clinopyroxene crystals (Fig. 13). Plagioclase is variably altered to sericite and minor calcite. Clinopyroxene is generally less altered than plagioclase but shows some replacement by green clay, chlorite, and goethite/hematite. Fe-Ti oxides are present throughout the sample and include very fine grained, oriented inclusions in some clinopyroxene crystals that probably formed by exsolution.
Figure 13. Photomicrograph (crossed polars) showing subophitic texture in diabase dike exposed near Heyls Hill. Random plagioclase crystals partly altered to calcite are intergrown with clinopyroxene showing higher birefringence. Width of view is ~2.5 mm.
CHAPTER 4: DAVIDSON METARHYOLITE

Overview

The Davidson metarhyolite and Pratt Hill quartzite have been the subject of controversy for nearly a century, due mainly to their fine-grained, recrystallized fabrics and close spatial association. The Pratt Hill quartzite is exposed only on the steep, north-facing slope of Pratt Hill (locality FS-161, Plate I and Figs. 4 and 7) and overlies the Davidson metarhyolite. The Davidson metarhyolite is exposed immediately adjacent to Pratt Hill, on both the west and east, as well as elsewhere in the northern part of field area (Plate I and Figs. 4 and 7). Many features typical of rhyolite lavas are well displayed throughout the Davidson metarhyolite, although they have been variably modified by metamorphic recrystallization, whereas the Pratt Hill quartzite lacks evidence for a volcanic origin.

Previous Work

In the past, most workers have assigned the Davidson metarhyolite and Pratt Hill quartzite to a single unit. Metamorphic rocks cropping out south of Mount Scott were interpreted by Taylor (1915) to be Precambrian quartzite xenoliths. Hoffman (1930) reinterpreted these rocks to belong to a shallow-level intrusion, which he named the Davidson Granophyre. Schoonover (1948) followed this interpretation but renamed the unit the Davidson Microgranite. In contrast, Ham et al. (1964) interpreted these rocks as hydrothermally altered lava and minor hornfelsic tuff of the Carlton Rhyolite Group. Sides and Miller (1982) first coined the informal term Pratt Hill quartzite and interpreted the protolith of the unit to be submature clastic sediments deposited along the unconformity between the Carlton Rhyolite and underlying...
gabbroic rocks (not exposed in the area of concern here). Moreover, Sides and Miller (1982) interpreted a portion of the Davidson metarhyolite located near the southwest shore of Lake Elmer Thomas, in the Hide-A-Way area, as part of the Pratt Hill quartzite.

Sides and Miller (1982) did not believe that the Pratt Hill quartzite was correlative with either the Meers Quartzite of Hoffman (1930) or the Tillman Metasedimentary Group of Ham et al. (1964), although they noted that all three of these units shared some compositional similarities. At the time Sides and Miller (1982) published their work, the Meers Quartzite was considered to represent metamorphosed sandstones occurring only as xenoliths in rocks of the Raggedy Mountain Gabbro and Wichita Granite Groups (Ham et al., 1964; Powell et al., 1980). Gilbert (1982a), in contrast, interpreted some examples of Meers Quartzite to represent sandstones deposited on the unconformable surface separating the Carlton Rhyolite from older, eroded gabbroic rocks, and he considered the rocks south of Mount Scott to be an argillaceous facies of Meers Quartzite occupying a similar stratigraphic position. Price (1998) and Price et al. (1998b) interpreted some of the outcrops considered by Sides and Miller (1982) as Pratt Hill quartzite to represent contact-metamorphosed rhyolite, but retained the term Pratt Hill quartzite for metasedimentary rocks lying between the Davidson metarhyolite and the main flow of Carlton Rhyolite above (termed the Fort Sill rhyolite herein).

**Field Characteristics**

The Davidson metarhyolite can be traced discontinuously along strike from west to east for ~9.25 km (Plate I and Figs. 4 and 7). The unit typically crops out in areas of lower elevation such as intermittent creek drainages. The thickness and total extent of the Davidson metarhyolite are unknown, and large parts of it are presumably buried underneath Permian deposits of the Post Oak Formation and Quaternary alluvium. To the south the Davidson metarhyolite is
stratigraphically overlain by the Fort Sill rhyolite or, where present, thin metasedimentary rocks (e.g., Pratt Hill quartzite). However, contacts with these overlying units are covered by water (e.g., Lake Elmer Thomas), vegetation, or thin soils. As previously discussed, margins of the Davidson metarhyolite are commonly truncated by intrusive granite.

Pervasive, delicate flow lamination with variable attitudes is present throughout the Davidson metarhyolite (Figs. 14A and 14B) and is commonly deformed by small-scale, complex flow folds, which is one of the defining characteristics of the unit. In hand sample, the flow lamination is generally defined by alternating pink and brown parallel laminae (Fig. 14A). The color differences are caused mostly by varying concentrations of feldspar and sericite in the pink laminae, versus abundant recrystallized quartz in the brown laminae, where hematite dust coating the mineral grains imparts a brown hue. Black laminae containing high concentrations of magnetite are also present (Fig. 15A). Steeply plunging, isoclinal to open flow folds have wavelengths $\leq 50$ cm and amplitudes $\leq 10$ cm (Fig. 15B). These features are common in most outcrops of the Davidson metarhyolite and are particularly well displayed in exposures along the northwest shore of Lake Elmer Thomas in the Wichita Mountains Wildlife Refuge (locality F, Fig. 7). There, progressive deformation during emplacement of the viscous lava has resulted in many refolded folds with highly complex fold geometries, similar to those documented in other parts of the Carlton Rhyolite Group (Eschberger et al., 2014; Hanson et al., 2014).

Rare, subangular basaltic inclusions $\sim 2$ cm long are present in places (Fig. 16A). Locally, flow-laminated and flow-folded metarhyolite grades into meter-scale areas of well-developed flow breccia. In the Hide-A-Way area (locality FS-160, Plate I and Figs. 4 and 7), the flow breccia consists of angular, flow-laminated metarhyolite clasts $\geq 2$ cm long (Fig. 16B). Similar flow breccia occurs in the upper parts of some of the other lava flows in the Carlton Rhyolite
Figure 14. (A) Cut slab of Davidson metarhyolite showing flow lamination. (B) Photomicrograph (plane light) of Davidson metarhyolite showing relict flow lamination overprinted by granoblastic intergrowth of quartz and alkali feldspar. Magnetite crystals (black) are also visible. Width of view is ~5 mm.
Figure 15. (A) Outcrop photo of Davidson metarhyolite showing black, magnetite-rich flow laminae. Note the small fault offsetting the laminae and the thin, irregular, cross-cutting magnetite veinlets. (B) Tight, steeply plunging flow folds deforming flow lamination in the Davidson metarhyolite.
Figure 16. (A) Basaltic inclusion within Davidson metarhyolite. Folded flow lamination is also visible. (B) Flow breccia in Davidson metarhyolite with angular, flow-laminated clasts.
(Eschberger et al., 2014; Hanson et al., 2014). Given the close proximity to overlying volcaniclastic metasedimentary rocks, the presence of flow breccia in this part of the Davidson metarhyolite is taken to indicate that the upper preserved part of the flow beneath the metasedimentary sequence is close to the original top of the flow.

Exposures at locality FS-159 of the Davidson metarhyolite west of the Hide-A-Way area (Plate I and Figs. 4 and 7) show crude, steeply plunging (near vertical) columnar jointing, which is approximately perpendicular to the erosional top of the flow (Fig. 17). The columns are locally overprinted by sheeting joints with variable attitudes, which are inferred to have developed due to volume changes during devitrification (cf., Bonnichsen and Kaufman, 1987; Hanson et al., 2014).

Thin magnetite- and quartz-rich veins cut parts of the Davidson metarhyolite. Magnetite veins are as much as 10 cm wide, although they are typically much thinner (Figs. 15A and 18A). Quartz veins are less common and generally <2 cm wide. Pink alteration haloes along some quartz veins contain disseminated magnetite grains intergrown with the recrystallized rhyolite groundmass (Fig. 18B). The quartz veins are in some cases cut by magnetite veins, indicating two separate phases of fluid migration through the Davidson metarhyolite. These types of veins are not seen elsewhere in the Carlton Rhyolite (Hanson, personal communication) and are inferred to have developed during contact metamorphism caused by intrusion of the Mount Scott Granite.
**Figure 17.** Outcrop of Davidson metarhyolite showing crude columnar jointing. Hammer for scale (circled) is approximately parallel to column long axes.
Figure 18. (A) Outcrop of Davidson metarhyolite with magnetite vein. (B) Outcrop of Davidson metarhyolite with quartz vein surrounded by pink alteration halo containing disseminated magnetite grains.
Mineralogy and Petrography

On fresh surfaces the Davidson metarhyolite ranges in color from light pink to brown or purple and typically weathers to dark-brown or buff. Both in hand sample and thin section the unit is generally aphyric. However, some samples contain <1% altered alkali feldspar phenocrysts that are typically ≤1 mm long and subhedral (Fig. 19). In some cases, the feldspar phenocrysts are euhedral and as much as 2.25 mm in length. In thin section, these phenocrysts are commonly replaced by sericite and/or very fine-grained quartz and are recognizable only by their rectangular outlines (Fig. 19). Rare examples show remnant chessboard albite twinning similar to that observed in alkali feldspar phenocrysts in the overlying Fort Sill rhyolite, discussed later. Zircon is present as an accessory phase with individual crystals as much as 0.11 mm long and commonly occurs in glomerocrystic intergrowths with relict alkali feldspar phenocrysts.

In thin section, one of the most striking features of the Davidson is its fine-grained, recrystallized fabric of granoblastic quartz and interstitial feldspar, which is mostly replaced by sericite (Fig 19). Individual quartz crystals average ~0.01 mm in size and make up ≥50% of the rock matrix. This texture is very similar to felsitic samples of Fort Sill rhyolite that have been mildly silicified and metamorphosed. The only difference is the slightly larger size of the granoblastic quartz crystals and altered feldspar in the groundmass of the Davidson metarhyolite, which reflects the higher degrees of metamorphism experienced by that unit. Disseminated anhedral magnetite grains 0.02 to 0.25 mm in size are present in most samples and comprise as much as 10% of the rock.

Metamorphic minerals are ubiquitous in thin section, although they are too fine-grained to be seen in hand sample and occupy <1% of the rock volume. Chlorite, muscovite, and biotite
Figure 19. Photomicrograph (plane light) of Davidson metarhyolite showing subhedral alkali feldspar phenocryst completely replaced by sericite. Note the well-developed granoblastic groundmass texture comprised of quartz intergrown with sericite. Width of view is ~5 mm.
are commonly present within the recrystallized groundmass and form microporphyroblasts as much as 0.2 mm long. Fibrolitic sillimanite ≤0.1 mm in length (Fig. 20A) was identified in the groundmass of a sample collected in the Lake Elmer Thomas Recreation Area (locality FS-60, Plate I and Figs. 4 and 7), northeast of Pratt Hill. Samples collected in the Hide-A-Way area (locality FS-160, Plate I and Figs. 4 and 7) contain rare subhedral to anhedral andalusite poikiloblasts ≤1.25 mm in size that are intergrown with quartz and, less commonly, biotite ≤0.15 mm in length (Fig. 20B). Metamorphic subhedral plagioclase ≤0.25 mm in length is present in some cases. It occurs within a quartz veinlet in a sample from the Hide-A-Way area and within the groundmass of a sample collected along the northwest shore of Lake Elmer Thomas (locality F, Fig. 7) in the Wichita Mountains Wildlife Refuge.

The presence of andalusite and sillimanite in the vicinity of Pratt Hill indicates that metamorphic conditions reached the hornblende hornfels and pyroxene hornfels facies. It should be noted that previous workers also reported andalusite within the Pratt Hill quartzite (Miller et al., 1982; Price et al., 1998b). Metamorphism may have occurred at lower grades where andalusite and sillimanite are absent in the Davidson metarhyolite, but the occurrence of these minerals may also be controlled by compositional variations. Formation of these aluminosilicate minerals in a metarhyolite requires development of alumina-oversaturated bulk compositions, which probably occurred by loss of alkalis during silicification and may have affected some samples more than others. A future systematic study might be able to map isograds across the Davidson metarhyolite outcrop area but would require detailed attention to bulk compositional variations.
Figure 20. (A) Photomicrograph (plane light) of Davidson metarhyolite showing fibrolitic sillimanite (red arrows) within granoblastic groundmass comprised of quartz intergrown with sericite. Width of view is ~2.5 mm. (B) Photomicrograph (plane light) of Davidson metarhyolite showing andalusite poikiloblast intergrown with quartz in center of view. Width of view is ~2.5 mm.
CHAPTER 5: VOLCANICLASTIC METASEDIMENTARY ROCKS

Overview

The Davidson metarhyolite is overlain by a discontinuous clastic metasedimentary unit dipping gently to the south (Plate I and Figs. 4, 6 and 7). As discussed in Chapter 4, part of this unit has been termed the Pratt Hill quartzite where it is exposed at the base of Pratt Hill (locality FS-161, Plate I and Figs. 4 and 7; Sides and Miller, 1982). Previously unrecognized clastic metasedimentary rocks stratigraphically equivalent to the Pratt Hill quartzite are exposed in the Hide-A-Way area (locality G, Fig. 7) and along an unnamed ridge farther west (locality B, Fig. 7). The clastic interval is ≥20 m thick at Pratt Hill (Sides and Miller, 1982), but the base is covered by Lake Elmer Thomas. The interval is only ~1 m thick west of the Hide-A-Way area. The clastic rocks are completely absent in places, suggesting they were deposited on an irregular erosional surface that developed on top of the Davidson metarhyolite. Some of these rocks consist of relatively pure quartzite similar to that at Pratt Hill, but coarse- to fine-grained rhyolitic volcaniclastic metasandstone and metasiltstone containing monocrystalline quartz, feldspar, and rhyolite lithic grains are also present. Coarse, monocrystalline quartz grains in these beds could not have been derived from the underlying Davidson metarhyolite and instead record influx of detritus from erosion of quartz-phyric rhyolite elsewhere in the developing volcanic pile. Volcaniclastic debris-flow deposits are intercalated with the fine-grained rocks and contain pebble-sized clasts of rhyolite and quartzite.
Pratt Hill Quartzite

The contact between the Pratt Hill quartzite and Davidson metarhyolite is covered by Lake Elmer Thomas. However, the contact with the overlying Fort Sill rhyolite is exposed on the steep, north facing slope of Pratt Hill (locality FS-161, Plate I and Figs. 4 and 7), where it strikes N60°E and dips 10° southeast (Fig. 6; Sides and Miller, 1982). The contact is sharp and can be traced for several meters along the cliff face but varies in elevation due to its irregular nature. On part of the northern slope of Pratt Hill the contact is close to water level. Toward the east it climbs ~20 to 30 m above the lake level and can be followed eastward to near a small, intermittent stream, beyond which the contact is concealed by talus and thin soil. To the west the quartzite thins dramatically and the contact with the Fort Sill rhyolite disappears below water level (Sides and Miller, 1982). The nature of the irregular contact led Schoonover (1948) to interpret Pratt Hill as an uplifted horst block bounded on the east and west by faults. A more likely interpretation is that the contact represents an irregular erosional surface with moderate relief that developed on top of the Davidson metarhyolite prior to eruption of the overlying Fort Sill rhyolite (Price et al., 1998b).

In hand sample, the Pratt Hill quartzite is generally gray to green and very fine grained (Fig. 21A), which gives the rock a sugary appearance. In thin section, the rock is composed of ~50 to 90% quartz grains that are very well sorted, with coarse silt to very fine sand-sized grains comprising most of the rock (Fig. 21B). Metamorphic recrystallization of quartz has imparted a well-developed granoblastic texture that overprints original grain shapes, although relict, well-rounded grains can still be identified in some samples. Very fine grained interstitial sericite and variable amounts of chlorite and green clay comprise most of the remaining rock volume.
Figure 21. (A) Cut slab of Pratt Hill quartzite. Irregular color pattern is the result of variations in the degree of recrystallization. (B) Photomicrograph (crossed polars) of Pratt Hill quartzite showing recrystallized granoblastic quartz and interstitial sericite. Width of view is ~1.25 mm.
Other minor components of the Pratt Hill quartzite observed in this study include rare andalusite porphyroblasts ≤0.625 mm long, in addition to muscovite and biotite porphyroblasts of similar size. In some cases, the biotite shows poikiloblastic texture. Disseminated anhedral magnetite and pyrite (≤0.25 mm) that have been altered to yellow limonite or goethite and red hematite also occur, and detrital zircon grains (≤0.08 mm) are distributed randomly throughout the rock.

Although bedding is not obvious in the field, some samples studied in thin section contain thin layers (mm- to cm-scale) composed of very well sorted, medium- to coarse-sand-sized quartz grains that grade into sericite-rich layers. Price et al. (1998b) described similar layering, which they interpreted as relict graded bedding. They also identified abundant small andalusite scattered within the finer grained layers and rare, larger andalusite porphyroblasts rimmed by sericite in the coarser grained layers. Price et al. (1998b) interpreted the more abundant andalusite in the finer grained layers to represent higher original clay content.

The Pratt Hill quartzite is capped by a ~1-m-thick, matrix-supported, polymict unit that lacks internal stratification and is directly overlain by the Fort Sill rhyolite. This unit is interpreted to be a debris-flow deposit. Pebble-sized, partly disaggregated clasts of Pratt Hill quartzite within the debris-flow deposit have released rounded silt grains into the adjacent matrix, which indicates that the protolith to the quartzite was at least partly unconsolidated during transport and deposition of the debris flow. The deposit also contains angular, pebble-sized clasts of quartz-phyric rhyolite that lack alkali feldspar phenocrysts. These rhyolite clasts are unlike the Davidson metarhyolite or the overlying Fort Sill rhyolite and must have come from a different source. Additional clasts include relict long-tube pumice ranging from ash-sized to >2 cm in length (Fig. 22). Some relict pumice clasts show flattening due to burial compaction...
Figure 22. Cut slab of polymict debris-flow deposit overlying the Pratt Hill quartzite. Note the large quartz-phyric rhyolite lithic clasts (R), long-tube pumice clast (P), and green-colored, fine-grained vitroclastic matrix.
(cf. Bull and McPhie, 2007) (Fig. 22). The matrix of the deposit consists of poorly sorted, silt- to sand-sized quartz and alkali feldspar grains intermixed with abundant fine-grained, recrystallized vitroclastic material. The vitroclastic material has been replaced by fine-grained, green phyllosilicates, giving the rock a green tint (Fig. 22). The coarser sand-sized quartz and alkali feldspar grains are inferred to represent reworked phenocrysts derived from erosion of rhyolite lava not exposed in the study area.

**Hide-A-Way Area**

A sequence of dominantly volcaniclastic metasedimentary rocks with some similarities to those described on Pratt Hill is exposed in a north-flowing intermittent stream in the Hide-A-Way area (locality G, Fig. 7; Fig. 23). The sequence dips 10 to 12° to the south, strikes roughly east to west, and is ~19 m thick. Extremely poor exposure impedes accurate bedding plane measurements, and the outcrops are limited to the actual creek bed. In addition to poor exposure, the sequence has a relatively strong metamorphic overprint that masks some primary features.

The Davidson metarhyolite is fairly well exposed in the Hide-A-Way area, and the southernmost outcrops of the unit in the intermittent stream are assumed to be very close to the erosional top of the flow. Above the stratigraphically highest Davidson outcrop, there is a mostly covered interval ~8.5 m thick (Fig. 23). In the middle of this interval, quartzite is very poorly exposed; it could possibly make up the entire interval, but this is speculative. The quartzite is gray-green in hand sample (Fig. 24A) and consists predominantly of recrystallized, coarse-silt-sized granoblastic quartz with fine-grained interstitial sericite and sparse, coarser crystals of muscovite (Fig. 24B). The quartz grains are well sorted and, despite the metamorphic overprint, relict rounded grains are still visible. Other constituents include detrital zircon, disseminated magnetite, and minor biotite porphyroblasts ≤0.15 mm in length. Laminae composed of very
Figure 23. Measured section of volcaniclastic metasedimentary rocks exposed in the Hide-A-Way area at locality G on Figure 7.
Figure 24. (A) Cut slab of Pratt Hill-type quartzite in the lower part of the volcaniclastic metasedimentary sequence exposed in the Hide-A-Way area. Planar lamination is visible running across the slab from upper left to lower right (saw marks run in the opposite direction). (B) Photomicrograph (crossed polars) of Pratt Hill-type quartzite exposed in the Hide-A-Way area showing recrystallized granoblastic quartz, interstitial sericite, and coarser muscovite crystals. Width of view is ~1.25 mm.
well sorted, medium sand-sized quartz grains with little interstitial sericite occur in places. This unit is lithologically identical to the Pratt Hill quartzite and is considered to be a westward extension of it (too small to show on the scale of Plate I and Figs. 4 and 7). The rapid westward thinning of the Pratt Hill quartzite is consistent with deposition in a small paleovalley that deepens to the east and was eroded into the underlying Davidson metarhyolite.

Above the covered interval is a poorly sorted, rhyolitic tuffaceous metasandstone ~3 m thick (Fig. 23). The unit is poorly exposed and no bedding or other sedimentary structures were observed in it. Approximately 15% of the rock is composed of angular to subrounded, medium-to coarse-sand-sized quartz and subordinate alkali feldspar grains (Fig. 25). Some of the alkali feldspar grains have been partly altered to sericite, and others show relict chessboard albite twinning. The remainder of the rock is dominantly a very fine-grained matrix of granoblastic quartz, alkali feldspar, rare plagioclase, and interstitial sericite with minor amounts of chlorite. The matrix material is inferred to mainly represent recrystallized vitroclastic debris and contains relict ash-sized, long-tube pumice clasts, sparse biotite and muscovite porphyroblasts ≤0.4 mm in size, and detrital zircon and disseminated magnetite ≤0.25 mm in size.

The tuffaceous metasandstone is overlain by a matrix-supported, polymict debris-flow deposit ~6.5 m thick (Fig. 23) that contains subangular to angular, pebble-sized clasts of aphyric rhyolite similar to the Davidson metarhyolite (Fig. 26); porphyritic rhyolite clasts containing quartz and alkali feldspar phenocrysts (Fig. 27); and quartzite clasts composed of well-rounded, well-sorted, fine-sand-sized quartz grains showing some granoblastic texture (Figs. 26 and 28). The quartzite clasts are slightly coarser grained and generally have less interstitial sericite than the Pratt Hill quartzite. Additionally, these subangular to angular clasts were well lithified during formation of the debris-flow deposit, which contrasts with evidence that the protolith to the
Figure 25. (A) Cut slab of lower unit of poorly sorted rhyolitic tuffaceous metasandstone exposed in the Hide-A-Way area. (B) Photomicrograph (crossed polars) of the same rock. Note the sand-sized quartz (Q) and alkali feldspar (F) grains in a very fine grained matrix. Width of view is ~5 mm.
Figure 26. (A) Photomicrograph (plane light) of polymict debris-flow deposit showing clasts of aphyric, Davidson-type metarhyolite (R) and quartzite (Qt) enclosed in a poorly sorted, silt-sized, quartz-rich matrix. Width of view is ~5 mm. (B) Same view as in A with crossed polars.
Figure 27. Cut slab showing porphyritic rhyolite lithic clasts (arrowed) in the lower part of the polymict debris-flow deposit exposed in the Hide-A-Way area.
Figure 28. Cut slab showing quartzite clast (lower right) and altered vitroclastic matrix in the upper part of the debris-flow deposit exposed in the Hide-A-Way area.
upper Pratt Hill quartzite was poorly consolidated when clasts from that unit were incorporated into the overlying debris-flow deposit on Pratt Hill. It is possible that the protolith to the Pratt Hill quartzite had undergone different degrees of lithification prior to deposition of the overlying beds or that the well-lithified quartzite clasts in the debris-flow deposit in the Hide-A-Way area were derived from a different source. Furthermore, porphyritic rhyolite clasts record influx of volcanic debris that is unlike Davidson metarhyolite and predates emplacement of the Fort Sill rhyolite, suggesting a more complex evolution of the developing volcanic pile in the area than has previously been recognized.

The matrix of the debris-flow deposit is nearly identical to the underlying tuffaceous metasandstone except that it also contains coarse-silt-sized quartz grains. The lower half of the unit is pink in hand sample (Fig. 27) and contains moderate amounts of interstitial sericite. Fine-grained, interstitial vitroclastic material increases significantly in the upper portion of the unit. The recrystallized vitroclastic material has been replaced by fine-grained green phyllosilicates, typically giving the rock a gray-green color in hand sample (Fig. 28). The increase in interstitial vitroclastic material appears to be gradational, suggesting that both the pink and gray-green parts of this interval represent a single debris-flow deposit. Two separate debris-flow deposits could be present, but extremely poor exposure precludes determination of contact relations. Nonetheless, this debris-flow interval occupies a similar stratigraphic position to the deposit that caps the Pratt Hill quartzite, but whether the debris-flow deposits correlate between the two areas is uncertain.

The debris-flow interval is overlain by a ~1-m-thick, rhyolitic tuffaceous metasandstone (Fig. 23) that contains relict long-tube pumice clasts as much as 4.75 mm long (Fig. 29). This unit is poorly sorted and contains 30 to 40% rounded, coarse-silt to fine-sand-sized quartz grains.
Figure 29. Photomicrograph (plane light) of poorly sorted, tuffaceous metasandstone in the upper part of the volcaniclastic metasedimentary sequence exposed in the Hide-A-Way area. A relict long-tube pumice clast is indicated. Quartz sand grains (Q) are visible, along with smaller amounts of alkali feldspar grains (F). Width of view is ~1.3 cm.
Medium to coarse, subangular to subrounded sand-sized quartz and subordinate alkali feldspar grains occur in amounts of 3 to 5%. Green metamorphic biotite ~0.3 mm in length and interstitial sericite, minor metamorphic plagioclase, and disseminated magnetite compose most of the remainder of the rock and are inferred to represent recrystallized vitroclastic material. Silt- and fine-sand-sized quartz grains from this unit have been intimately mixed with the base of the Fort Sill rhyolite, creating a peperite ~1 m thick (Fig. 23), which indicates that the sediment was wet and unconsolidated during emplacement of the overlying lava flow (see Chapter 6).

**West of the Hide-A-Way Area**

Along an unnamed ridge ~2.3 km west of Pratt Hill is another exposure of rhyolitic volcaniclastic metasedimentary rocks that dip 12° to the south-southwest (locality B, Figs. 7 and 8). The outcrop consists mostly of a ~1-m-thick, rhyolitic volcaniclastic metasandstone with thin relict planar bedding and lamination (Fig. 30). This unit can be traced discontinuously along strike for ~94 m (Fig. 8). The metasandstone is poorly sorted and composed dominantly of subrounded to rounded, coarse-sand-sized alkali feldspar and quartz grains in roughly equal proportions (Fig. 31A and 31B), with interstitial recrystallized, coarse-silt-sized quartz and alkali feldspar grains. The interstitial alkali feldspar grains have largely been replaced by sericite. Minor biotite ≤0.25 mm in length is present along with detrital zircon and disseminated magnetite. In places, the unit is capped by a metasiltstone 5 to 10 cm thick that is composed of ≥50% medium- to coarse-silt-sized quartz grains with the rest being interstitial sericite (Fig. 31A and 31B). The upper contact of the unit with the Fort Sill rhyolite is covered by thin soil and grass. As previously discussed, the base of the unit has been intruded by Mount Scott Granite (Fig. 8).
Figure 30. Outcrop of rhyolitic volcaniclastic metasedimentary rocks exposed west of the Hide-A-Way area showing thin planar bedding and lamination.
Figure 31. (A) Planar-bedded rhyolitic volcaniclastic metasandstone capped by a thin veneer of metasiltstone. (B) Photomicrograph (crossed polars) of contact between metasandstone and metasiltstone shown in Fig. 31A, with quartz and alkali feldspar grains visible in metasandstone. Width of view is ~1.6 cm.
CHAPTER 6: FORT SILL RHYOLITE

Introduction

The Davidson metarhyolite and the discontinuous interval of volcaniclastic metasedimentary rocks above it are overlain by the distinctive Fort Sill rhyolite. In contrast to the Davidson metarhyolite, the Fort Sill rhyolite contains abundant quartz and alkali feldspar phenocrysts and displays a vertical zonation defined by changes in groundmass texture and outcrop characteristics. This unit forms the majority of rhyolite exposed in the Fort Sill area (Plate I and Figs. 4 and 32) and is the longest documented flow in the Carlton Rhyolite Group.

Previous Work

Beginning with Taff (1904), most of the fieldwork done on what I refer to as the Fort Sill rhyolite has been reconnaissance in nature. Taff (1904) referred to the distinctive topography of rounded, grass-covered hills underlain by the rhyolite (Fig. 32) as the Carlton Mountain Group physiographic region and considered the rocks exposed there to be granite porphyry and associated aporhyolite (an old term for devitrified, originally glassy rhyolite). The name Carlton Mountain now refers only to a single peak among a series of hills in the area; this peak is largely within an artillery impact zone in Fort Sill and strictly off limits to the public. Hoffman (1930) interpreted the rocks underlying the hills in the Fort Sill area to be of shallow intrusive origin and named them the Carlton Granophyre. Schoonover (1948) renamed the unit Carlton Rhyolite. Ham et al. (1964) included parts of the Fort Sill rhyolite in their study on the basement rocks of southern Oklahoma and introduced the term Carlton Rhyolite Group to include all related surface
Figure 32. Photograph from the top of Mount Scott looking south toward Fort Sill Military Reservation. The characteristic topography of rounded, grass-covered hills underlain by Fort Sill rhyolite is well displayed by Pratt Hill, Jones Ridge, and Carlton Mountain. The base of the Fort Sill rhyolite is exposed on the steep, north-facing cliff of Pratt Hill. Location of the Hide-A-Way area is also indicated.
and subsurface rhyolite in the Wichita igneous province. However, they chose Bally Mountain, in the Slick Hills to the north (Fig. 1), as the type section of the group, because a thick, well-exposed rhyolite sequence occurs in that area (Hanson et al., 2014). In the first geochemical study of the Carlton Rhyolite, Hanson (1977) included samples from the Fort Sill rhyolite. In their study of the Pratt Hill quartzite, Sides and Miller (1982) included a portion of Fort Sill rhyolite that caps that hill. Gilbert (1982b), Miller et al. (1982), and Gilbert (1986) briefly described some of the Fort Sill rhyolite in the Mount Scott Campground, Hide-A-Way, and Medicine Bluff areas, respectively. Additionally, Price (1998) included areas of the Fort Sill rhyolite in his study on the Mount Scott Granite.

Field Characteristics and Devitrification Textures

The Fort Sill rhyolite can be traced along strike in a roughly east to west direction for ~18.5 km before becoming covered or being truncated by intrusive granite; thus its original extent is unknown (Plate I and Fig. 4). Its base is poorly exposed along strike in limited areas where it overlies the Pratt Hill quartzite at Pratt Hill and associated volcaniclastic metasedimentary rocks to the west (Fig. 7). In those areas, the rhyolite dips ~10 to 12° to the south (Fig. 6), as defined by contacts with the underlying bedded metasedimentary rocks. The top is erosional, and the unit has a minimum exposed thickness of ~100 m at Medicine Bluffs. The total thickness of the Fort Sill rhyolite cannot be determined based on available data. One problem is that a cross-section from the exposed base at Pratt Hill southward across the field area to Signal Mountain yields an unreasonable thickness of over 1 km (only part of this cross-section is shown in Figure 6). This assumes a constant dip of 10° to the south, as measured at the contact with the Pratt Hill quartzite. If the dip shallows to the south the rhyolite could be considerably less than 1 km thick. Furthermore, the amount of vertical displacement along the Deer Creek
Canyon Fault Zone is unknown, and there is also a second prominent lineament to the south along Brush Canyon (Plate I and Fig. 4) that parallels the Deer Creek Canyon Fault Zone. That lineament could not be investigated because it lies within the artillery impact zone. It is possible that the lineament along Brush Canyon represents another fault zone with unknown vertical displacement that offsets the Fort Sill rhyolite.

At its northern outcrop margin the Fort Sill rhyolite is deformed by the Little Medicine Creek Fault Zone and is intruded by Mount Scott Granite. The unit is either intruded by granite or covered by Permian sedimentary rocks and Quaternary alluvium at its southern, eastern, and western outcrop margins (Plate I and Fig. 4).

**Vertical Zonation**

In the Slick Hills to the north of the Fort Sill area, individual flows within the Carlton Rhyolite typically display a readily identifiable vertical cooling zonation defined by changes in groundmass textures and outcrop features (Hanson et al., 2014), as described in Chapter 2. Likewise, the Fort Sill rhyolite demonstrates a vertical zonation (Fig. 5), although some features contrast markedly with those described in units exposed in the Slick Hills. Three main zones characterize the Fort Sill rhyolite and are described below. Groundmass textures in the lowest part of the rhyolite show a clear metamorphic overprint, with development of granoblastic quartz and feldspar. The textures are similar to those developed in the Davidson metarhyolite, but the overprint progressively decreases upward. Higher in the Fort Sill rhyolite, there is little or no evidence for contact metamorphism.
Lower Part of the Flow

In places, a very subtle vertical zonation in the Fort Sill rhyolite is present in the lower part of the flow and is defined by changes in groundmass textures visible at thin-section scale. This vertical zonation is best expressed where the base of the Fort Sill rhyolite is exposed at Pratt Hill (locality FS-144, Plate I and Figs. 4 and 7). There, the groundmass in the basal ~0.5 m of the flow shows relict perlitic texture, indicating the original presence of glass. Although the perlitic texture has a strong metamorphic overprint, the diagnostic curved, onion-skin-like cracks are still readily apparent (Fig. 33A).

Immediately above the basal glassy zone, the groundmass in a transitional zone making up the next few meters of the flow is characterized by fine-scale snowflake texture (Fig. 33B), which is a devitrification texture defined by optically continuous patches of micropoikilitic quartz surrounding numerous feldspar microlites (Anderson, 1969). Anderson (1969, 1970) considered snowflake texture to be a diagnostic feature of welded ignimbrites. However, Green (1970) pointed out that the texture is common in lava flows, and experiments by Lofgren (1971) showed the texture to be a general feature resulting from the devitrification of silicic glass. Snowflake texture has been reported to occur within many other lava flows within the Carlton Rhyolite Group (e.g., Bigger and Hanson, 1992; Philips, 2002; Burkholder, 2005; Eschberger et al., 2014).

Within this transitional zone rare, ovoid amygdules as much as 0.7 mm across are present and are lined with drusy quartz and filled with anhedral Fe-Ti oxides ~0.05 mm across, in addition to very fine grained green to yellow clay (Fig. 33B). Another feature of the transitional zone is a very delicate flow lamination that wraps quartz and alkali feldspar phenocrysts and is parallel to the base of flow (Fig. 34A). This transitional zone grades rapidly
Figure 33. (A) Photomicrograph (plane light) of relict perlitic texture from the base of the Fort Sill rhyolite exposed on Pratt Hill. Very fine grained quartz and alkali feldspar mosaic in the groundmass formed during devitrification has been recrystallized during metamorphism, with some secondary silicification. Secondary silica and very fine grained opaque granules outline relict perlitic cracks. Width of view is ~5 mm. (B) Photomicrograph (crossed polars) of a sample from the transition zone between the originally glassy base and felsitic interior of the Fort Sill rhyolite on Pratt Hill. Note the fine-scale snowflake groundmass texture and ovoid amygdule (arrow) lined with drusy quartz and filled with green-yellow clay. Quartz (Q) and partly silicified alkali feldspar (F) phenocrysts are also visible. Width of view is ~5 mm.
into the homogenous interior of the flow, which is mostly characterized by felsitic groundmass texture (Fig. 34B).

In addition to the originally glassy, perlitic base exposed on Pratt Hill, the base of the Fort Sill rhyolite is also exposed in a small drainage in the Hide-A-Way area west of Pratt Hill, where the rhyolite overlies the clastic metasedimentary interval (locality G, Fig. 7). Despite poor exposure, the basal ~1 m can be seen to consist of a discontinuous zone of peperite. The peperite contains angular to subangular fragments of rhyolite as much as ~5.5 cm across intimately mixed with rounded to subrounded silt- and fine-sand-sized quartz grains (Figs. 35A and 35B). Some of the rhyolite fragments are flow laminated. Immediately above the basal peperite, thin fractures extending at least 1.5 m up into coherent rhyolite are filled with similar sedimentary quartz grains (Fig. 36). Together, these features indicate that the rhyolite lava flowed over wet, unconsolidated sediment, causing quench fragmentation at the base and upward injection of fluidized sediment into fractures in the lava (e.g., Kokelaar, 1982). The base of the rhyolite in this area, as at Pratt Hill, contains a relatively strong metamorphic overprint with granoblastic quartz developed in the groundmass of some samples. The metamorphic overprint appears to be more intense in the Hide-A-Way area and tends to mask the vertical zonation in groundmass textures documented at Pratt Hill.

**Flow Interior**

The majority of outcrops of the Fort Sill rhyolite represent the interior of a large, tabular flow, and columnar jointing is visible in several places above the basal, originally glassy and transitional zones, including exposures at Pratt Hill. Columns are as much as 1.5 m wide and plunge steeply, approximately perpendicular to the base of the flow, although there is some
Figure 34. (A) Photomicrograph (plane light) of flow lamination wrapping a quartz phenocryst in the basal transition zone of the Fort Sill rhyolite exposed on Pratt Hill. The quartz phenocryst has been tectonically fractured. Width of view is ~5 mm. (B) Photomicrograph (crossed polars) showing characteristic felsitic groundmass texture in the interior of the Fort Sill rhyolite exposed on Pratt Hill. A quartz phenocryst is visible in top left corner. Width of view is ~5 mm.
Figure 35. (A) Cut slab of peperite at the base of the Fort Sill rhyolite exposed in the Hide-A-Way area showing angular to subangular rhyolite clasts set in a recrystallized matrix of silt- and sand-sized grains of quartz. Dark gray quartz phenocrysts are visible in the rhyolite. (B) Photomicrograph (plane light) of peperite. Note the silt grains injected between fractured rhyolite. FSr = Fort Sill rhyolite. Width of view is ~5 mm.
Figure 36. Cut slab of Fort Sill rhyolite overlying the basal peperite showing a fracture filled with recrystallized silt- and sand-sized quartz grains (arrow). Dark gray quartz and pink alkali feldspar phenocrysts are visible in the rhyolite.
variation in plunge. The best examples occur at Medicine Bluffs (Plate I and Figs. 4 and 37) where a section of the flow ~100 m thick above the basal zone is well exposed in steep cliffs carved by Medicine Creek (Gilbert, 1986). Well-developed columns also occur on parts of Jones Ridge and Thompson Hill (Fig. 38). Development of these regular columns points to uniform cooling of a single, thick flow.

Parts of the flow interior are characterized by a uniform, unbanded felsitic appearance in both hand sample and thin section (Fig. 34B). The transition from the lower, originally glassy chilled margin into homogeneous felsitic rhyolite is well displayed on Pratt Hill, as noted above. However, the interior of the rhyolite in many other places exhibits discontinuous flow banding, in which individual bands are only traceable for ≤1 m (Fig. 39). The banding generally shows highly variable attitudes and in places is clearly deformed by meter-scale flow folds, although poor exposure due to thick lichen cover and manganese staining precludes determination of fold geometries. The discontinuous banding is particularly obvious along Jones Ridge and on Thompson Hill (localities FS-131, FS-136, and FS-137, Plate I and Figs. 4 and 7). Pink, planar domains that range from 0.5 mm to 4 cm wide and are contained within gray to dark-brown rhyolite define the banding. Many of the pink bands show flame-like terminations and hence could be termed fiamme (Figs. 40 and 41), using this term in the nongenetic sense of Bull and McPhie (2007).

In thin section, the groundmass of the gray to dark-brown rhyolite shows both fine-grained felsitic and snowflake textures in some samples. The pink bands consist partly of a distinctive intergrowth of quartz and alkali feldspar that is significantly coarser than the adjacent groundmass in the gray to dark-brown bands (Figs. 41 and 42A). The texture in the pink bands is partly spherulitic, with randomly oriented to radiating tridymite crystals (now inverted to quartz).
Figure 37. (A) Columnar jointing in the interior of the Fort Sill rhyolite exposed at Medicine Bluffs. Height of the bluff shown in the photograph is ~100 m. (B) Closer view of columnar jointing in the same area. Width of columns is ~1 to 2 m.
Figure 38. Columnar jointing in the interior of the Fort Sill rhyolite exposed at Thompson Hill (Plate I and Figs. 4 and 7), ~15 km west of Medicine Bluffs. Width of columns is ~1.5 m. Hammer (circled) for scale.
Figure 39. Outcrop of discontinuous flow banding in the interior of the Fort Sill rhyolite on Jones Ridge.  Pencil points to a thin, discontinuous pink flow band that tapers to each side.
Figure 40. Cut slab from the interior of the Fort Sill rhyolite on Jones Ridge showing discontinuous pink flow bands with flame-like terminations (black arrows) alternating with gray bands. Red arrows point to discordant pink domains cutting across the main banding and connecting adjacent pink bands. Dark gray quartz and pink alkali feldspar phenocrysts are visible in the rhyolite.
Figure 41. Photomicrograph (plane light) of sample in Fig. 40 with pink flow band showing coarse devitrification texture in the center of the view and gray bands showing delicate flow lamination to each side. Main banding is vertical in this view. Note the flame-like terminations of the pink band (black arrow) and discordant devitrification domains (red arrows) that cut across the flow lamination in the gray bands at a high angle. Quartz phenocrysts (Q) are clear and alkali feldspar phenocrysts (F) are cloudy. Width of view is ~2 cm.
as much as 0.38 mm in length (Fig. 42B). The presence of tridymite, a high-temperature polymorph of silica, indicates that the internal temperature of the rhyolite was above 870° C when the flow came to rest (Deer et al., 2004), assuming the tridymite formed within its stability range (cf. Hanson and Eschberger, 2014). Radial, coalescing spherulites ≤0.75 mm in diameter dominate the texture in some cases, and axiolitic spherulites occur along the inner boundaries of many of the pink bands (Fig. 42B). Along the outer margins of the bands against dark-gray rhyolite, laminae defined by opaque microlites have, in places, been deformed into microscopic tight to isoclinal flow folds and partly incorporated into the pink bands (Fig. 42B). Discordant domains with identical coarse devitrification textures extend from some pink bands at high angles and cross-cut or connect with adjacent bands (Figs. 40 and 41). Such features are inconsistent with the interpretation that the discontinuous pinks bands are highly flattened pumice formed within a strongly welded ignimbrite. Discontinuous lenticular domains somewhat similar to the discontinuous bands in the Fort Sill rhyolite have been described by Dadd (1992) within extensive Devonian silicic lava flows in southeastern Australia. As in the Fort Sill rhyolite, the features documented by Dadd (1992) show flame-like terminations and have coarser grained devitrification textures than adjacent parts of the lava. Dadd (1992) attributed these discontinuous domains to the concentration of volatiles along shear planes developed during laminar viscous flow, with subsequent selective devitrification affecting the volatile-rich domains (cf. Bull and McPhie, 2007). I interpret the discontinuous bands with flame-like terminations in the interior of the Fort Sill rhyolite to have formed in a similar manner. Sides and Miller (1982) previously recognized fiamme-like features in the lower part of the Fort Sill rhyolite in the Pratt Hill area and used these features to support emplacement of the unit as an ignimbrite. I disagree with this interpretation for the reasons given above.
Figure 42. (A) Photomicrograph (crossed polars) of pink band from the interior of the Fort Sill rhyolite on Jones Ridge showing coarse devitrification texture that consists of a distinctive quartz and alkali feldspar intergrowth. Q = quartz phenocrysts. Width of view ~5 mm. (B) Photomicrograph (plane light) of same view as in A. Note randomly oriented tridymite needles (inverted to quartz) and axiolitic spherulites growing inward from the margins of the pink band. Along the outer margins of the pink band, against dark-gray rhyolite, laminae defined by opaque microlites have been deformed into tight to isoclinal flow folds and partly incorporated into the pink band. Width of view is ~5 mm.
**Upper Part of the Flow**

To the northwest of Medicine Bluffs, the rhyolite is also well exposed in the Heyls Hill-Rumbough Hill-Apache Ridge area (locality FS-88, Plate I and Fig. 4). In that area, flow banding is unusually well developed and differs significantly from that described above from the interior of the rhyolite. Near the top of Heyls Hill, individual flow bands lack flame-like terminations and can be traced continuously for several meters in zones as much as 10 m thick. They are deformed in places by steeply plunging, open flow folds with wavelengths of as much as 2 to 3 m (Fig. 43A). Small-scale upright, open flow folds with wavelengths ≤10 cm are present along Apache Ridge (Fig. 43B).

Flow bands in this part of the flow are defined by alternations of orange-gray, felsitic rhyolite and dark green to gray-green rhyolite representing altered glass; the thicker bands internally show a delicate, fine-scale flow lamination (Fig. 44A). In thin section, the banding is overprinted by well-developed snowflake texture. Flow lineation is developed on flow-band surfaces (Fig. 44B), and local areas of flow breccia ~1 m across are also present. This combination of features, including the relative abundance of original glass and the presence of flow breccia, suggests that the outcrops in the Heyls Hill-Rumbough Hill-Apache Ridge area are in the original upper part of the rhyolite flow.

**Mineralogy and Phenocryst Textures**

Modal analyses for 15 representative samples from the Fort Sill rhyolite and the two hypabyssal rhyolite bodies that intrude it are given in Table 1; sample locations are shown in Plate I and Figures 4 and 7. Total phenocryst abundances for the Fort Sill rhyolite range from 11.6 to 29.0 %.
Figure 43. (A) Steeply plunging, open flow fold in the upper part of the Fort Sill rhyolite on Heyls Hill. (B) Upright, open flow folds in the upper part of the Fort Sill rhyolite on Apache Ridge.
Figure 44. (A) Cut slab from the upper part of the Fort Sill rhyolite at Heyls Hill showing green, originally glassy band at top in contact with orange-gray band below that shows a delicate internal flow lamination. Dark gray quartz and pink alkali feldspar phenocrysts are visible. (B) Flow lineation developed on a flow band surface in the upper part of the Fort Sill rhyolite exposed on Apache Ridge.
### Table 1. Modal analyses of rhyolite samples from the Fort Sill area.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Alkali feldspar (%)</th>
<th>Quartz (%)</th>
<th>Oxide (%)</th>
<th>Groundmass (%)</th>
<th>Alkali feldspar size (mm)</th>
<th>Quartz size (mm)</th>
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<td></td>
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<tr>
<td>FS-18</td>
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<td>80.8</td>
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</table>
Alkali feldspar phenocrysts are the dominant phase in most samples, with abundances ranging from 7.2 to 19.6%. These crystals are as much as 7 mm in length and range from euhedral to anhedral but are most commonly subhedral. Carlsbad twinning is common, particularly in euhedral to subhedral crystals. Some of the larger feldspar phenocrysts have been partly resorbed, which imparts a spongy texture and indicates reaction with the melt in the magma chamber prior to eruption or during magma ascent. Variable alteration to sericite is very common and chlorite has partially replaced some phenocrysts, indicating some element mobility during alteration. Very fine-grained hematite inclusions within the alkali feldspar phenocrysts gives them a pinkish hue, and similar hematite “dust” permeates the groundmass. Many alkali feldspar phenocrysts have been wholly or partly replaced by chessboard albite, indicating Na-metasomatism has affected those crystals (e.g., Smith, 1974). Rare plagioclase phenocrysts with albite twinning occur in places and are generally found as single isolated phenocrysts ≤1 mm in size and less commonly as a component in glomerocrysts.

Quartz phenocrysts comprise 2.6 to 9.4% of the rhyolite, with crystals as much as 3 mm in diameter. Some phenocrysts retain the dipyramidal outline of β-quartz, but many are rounded and extensively embayed. The quartz crystals typically show diffuse margins that poikilitically enclose microlites within the adjacent groundmass, which is inferred to result from small-scale silica mobility during devitrification. The Fort Sill rhyolite contains many examples of quartz phenocrysts with elongated, tube-like embayments with bulbous tips (Fig. 45A) that are thought to result from “bubble drilling,” as produced experimentally by Donaldson and Henderson (1988). These workers theorize that small-scale convection of melt induced by non-equilibrium conditions near a bubble-crystal boundary can increase rates of locally enhanced dissolution of the crystal.
Granophyre inclusions as much as 2.75 mm across were also found in several samples in different parts of the Fort Sill rhyolite (Fig. 45B) and are inferred to have been derived from zones of sidewall crystallization that developed in the magma chamber prior to eruption. Mafic silicate phenocrysts as much as ~2 mm long have been completely replaced by green or brown clay and/or magnetite, hematite, goethite, limonite, leucoxene, chlorite, and more rarely, calcite (Fig. 46A). Based on their outlines, the primary mafic phase was probably pyroxene, although fayalite may also have been present. The mafic silicate phenocrysts are only found in some samples and generally occur in amounts of <1%. They are typically not visible on rock slabs and were not point counted.

Fe-Ti oxides, which range in abundance from 0.6 to 2.8 %, are disseminated throughout most samples and are variably altered to hematite and leucoxene. They are mostly anhedral and vary considerably in size but are generally <1 mm. Larger titanomagnetite crystals have octahedral outlines in some cases.

Glomerocrysts are uncommon and generally consist of two or three alkali feldspar and quartz phenocrysts as much as 5 mm in length (Fig. 46B). However, Fe-Ti oxides along with associated zircon are components of some glomerocrysts, as are quartz, rare plagioclase, and mafic silicate pseudomorphs (Fig. 46A). Subhedral to anhedral zircon is a common accessory phase in the Fort Sill rhyolite, where it has a particular affinity for Fe-Ti oxides. Isolated zircon crystals occur in the groundmass but are most commonly found adhering to the margins of Fe-Ti oxide crystals.

Secondary fluorite crystals as much as 0.5 mm in size partially fill rare amygdules (Fig. 47) or are present in quartz-rich veinlets in samples collected near contacts with intrusive granite. Fluorite is probably more common than was observed because it is easily overlooked during
Figure 45. (A) Photomicrograph (plane light) of embayed quartz phenocryst. Note the bulbous tips of the embayments. Width of view is ~2.5 mm. Flow lamination is visible in the adjacent groundmass and an alkali feldspar phenocryst is present in the upper right. (B) Photomicrograph (crossed polars) of granophyre inclusion contained in groundmass showing snowflake texture. Note coarser flow band with randomly oriented tridymite to the right. Width of view is ~5 mm.
Figure 46. (A) Photomicrograph (crossed polars) of a glomerocryst composed of a mafic silicate pseudomorph together with primary magnetite (partially replaced by hematite) and zircon (red arrow). The mafic silicate has been completely replaced by very fine grained green-brown clay intergrown with hematite and leucoxene. Note the coarse flow lamination (green arrow) wrapping the glomerocryst and the well-developed snowflake texture in the rest of the groundmass. Width of view is ~2.5 mm. (B) Photomicrograph (plane light) of glomerocryst composed of alkali feldspar (cloudy) and quartz (clear). Width of view is ~5 mm.
Figure 47. (A) Photomicrograph (plane light) of amygdule that is lined with drusy quartz and filled with fluorite (red arrows), secondary titanomagnetite, and very fine grained green-yellow clay. Q = quartz phenocryst. Width of view is ~2.5 mm. (B) Photomicrograph (crossed polars) of same view as in A. Note the fine-scale snowflake texture in the groundmass.
routine petrography. Its abundance is consistent with the A-type geochemical compositions of the rocks (see Chapter 7).

**Zones of Hydrothermal Alteration**

Zones of intense hydrothermal alteration are locally present in some exposures of Fort Sill rhyolite. Highly altered rhyolite in a zone ~100 m wide is exposed along the north bank of Medicine Creek (Schoonover, 1948), directly across from Medicine Man’s Walk, which is the name given to the saddle between two parts of Medicine Bluffs. Domains of white to light-gray or green rhyolite ~2 cm to ~1 m wide trend N20°W to N45°W within the altered zone, and are in contact with less altered brick-red rhyolite (Fig. 48A). The altered zone is less resistant to erosion than the surrounding unaltered rhyolite, creating a slight depression. Alkali feldspar phenocrysts and feldspar in the groundmass have been completely replaced by very fine grained green clay and white mica. The altered feldspar phenocrysts have been partly dissolved away, leaving small rectangular pits (Fig. 48B). Quartz phenocrysts have not been altered and stand out in relief on weathered surfaces. A similar zone of highly altered gray to green rhyolite at least ~3 m long and ~0.5 m wide was found on the saddle between Heyls Hill and Rumbough Hill but is poorly exposed. Schoonover (1948) reported similar alteration on Mount Hinds but did not give any descriptive details. The alteration only occurs locally and its origin is unknown. Schoonover (1948) and Gilbert (1986) report the presence of a diabase dike and quartz veins in Medicine Man’s Walk, and Schoonover (1948) inferred that the alteration of rhyolite across the creek from that feature was related to intrusion of the diabase dike. However, this type of alteration is not present elsewhere in the field area where diabase dikes can be directly observed cutting Fort Sill rhyolite, nor is it generally present where diabase intrudes other felsic units in the Wichita igneous province. An alternative and more likely possibility is that the hydrothermal alteration
was caused by fluids that were released during intrusion of Mount Scott Granite and migrated along zones of weakness in the rhyolite. The diabase dike in Medicine Man’s Walk likely followed the same zone of weakness that focused the hydrothermal alteration in that area.
Figure 48. (A) Hydrothermally altered Fort Sill rhyolite bordered by less altered brick-red rhyolite on the north bank of Medicine Creek. Dark gray quartz phenocrysts are visible in the altered rhyolite. (B) Cut slab of hydrothermally altered Fort Sill rhyolite showing altered alkali feldspar phenocrysts and fresh, dark gray quartz phenocrysts.
CHAPTER 7: GEOCHEMISTRY

Introduction

Geochemical analyses were carried out on 15 representative samples from the Fort Sill rhyolite, three from the Davidson metarhyolite, one from each of the two hypabyssal rhyolite intrusions, and one from the Pratt Hill quartzite. Analytical procedures are described in Chapter 1. The data are shown in Table 2 with major elements normalized to 100% on a volatile-free basis. Sample locations are shown on Plate I and Figures 4 and 7.

Primary igneous chemical compositions and trends in ancient igneous rocks may be disturbed by secondary alteration. Samples from the Davidson metarhyolite show a strong metamorphic overprint and ubiquitous secondary silicification and sericitization as described in Chapter 4, and geochemical data from this unit should therefore be treated with caution. Samples from the Fort Sill rhyolite are less altered, particularly away from intrusive granite contacts. However, many thin sections from the Fort Sill rhyolite contain chessboard albite that has replaced alkali feldspar phenocrysts, providing petrographic evidence for alkali metasomatism. Some samples also show varying degrees of sericitization. As such, care must be taken when interpreting the geochemical data from this unit as well, particularly with respect to Na$_2$O and K$_2$O contents and mobile trace elements such as Rb, Ba, and Sr.

In order to give an idea of compositional ranges and magmatic affinities shown by the rhyolites as a whole, data from this study are plotted with data from Hanson et al. (2014) for 35 samples of Carlton Rhyolite exposed in the Slick Hills. Also included are data from Price (1998) for two samples from rhyolite dikes that cut Wichita granite, two samples from rhyolite xenoliths contained within the granite, and two samples from the Davidson metarhyolite. Additional data
Table 2. Geochemical data for Carlton Rhyolite in the Fort Sill area.

<table>
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<tr>
<th>Sample</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>P2O5</th>
<th>TiO2</th>
<th>Total*</th>
<th>Ni (ppm)</th>
<th>Zn (ppm)</th>
<th>Cu (ppm)</th>
<th>Co (ppm)</th>
<th>Cr (ppm)</th>
<th>Ni (ppm)</th>
<th>Zn (ppm)</th>
<th>Cu (ppm)</th>
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<th>Cu (ppm)</th>
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<td>0.25</td>
<td>0.12</td>
<td>6.35</td>
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<tr>
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<td>0.12</td>
<td>6.35</td>
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* Total includes all elements, expressed as wt%.

Table 2. Geochemical data for Carlton Rhyolite in the Fort Sill area.
from a suite of representative samples from Wichita granites analyzed by Price (1998) are shown for the purposes of comparison.

**Major Elements**

Harker variation diagrams for the major elements are shown in Figures 49 to 56. The Davidson metarhyolite and Fort Sill rhyolite have relatively high silica contents, ranging from 76.64 to 77.92 wt % (including data from Price, 1998), and 75.50 to 78.33 wt %, respectively. The two hypabyssal rhyolite intrusions have lower silica contents at 72.62 wt % and 73.38 wt %. The high silica contents for the Davidson metarhyolite are consistent with petrographic evidence for secondary silicification. Samples from the Fort Sill rhyolite and the hypabyssal rhyolite intrusions show little to no petrographic evidence for secondary addition of silica, and their silica values are inferred to be close to primary igneous compositions.

Overall, the data for the rhyolites in the Fort Sill area show decreasing TiO₂, Al₂O₃, FeO, MgO, CaO, and P₂O₅ with increasing SiO₂. These trends are best defined by TiO₂, Al₂O₃, and FeO, although there is considerable scatter in the Harker diagrams, which is likely at least partly the result of alteration. The trends, however, are broadly consistent with fractional crystallization or progressive partial melting of source rocks. Evidence that element mobility during alteration has caused at least some of the scatter in FeO and MgO is seen in thin section, where secondary minerals have replaced primary mafic silicates in all of the samples.

The range in data for the Fort Sill rhyolite suggests that this flow formed by eruption of compositionally heterogeneous magma. The Fort Sill rhyolite and Davidson metarhyolite show broadly similar compositions on the Harker diagrams. However, Al₂O₃ contents for the three samples of Davidson metarhyolite analyzed in this study are higher than those in the Fort Sill
Figure 49. Harker diagram for TiO₂, including the legend for symbols used for all geochemistry diagrams.
Figure 50. Harker diagram for $\text{Al}_2\text{O}_3$.

Figure 51. Harker diagram for FeO.
Figure 52. Harker diagram for MgO.

Figure 53. Harker diagram for CaO.
Figure 54. Harker diagram for P$_2$O$_5$.

Figure 55. Harker diagram for Na$_2$O.
Figure 56. Harker diagram for $K_2O$. 
rhyolite, which is probably at least partly due to preferential loss of alkalis during metamorphism and alteration of the Davidson metarhyolite.

Na₂O and K₂O do not show well-defined trends on the Harker diagrams. Scatter in the data is interpreted to be due to alkali mobility during secondary alteration, which is also evident on the diagram of Hughes (1972), where the three samples of the Davidson metarhyolite analyzed in this study plot outside the normal igneous spectrum (Fig. 57). Note that these three samples appear to have lost Na₂O relative to the other samples (Fig. 55), which supports the interpretation that some of the scatter in Al₂O₃ in these samples is the result of alkali mobility.

In terms of major elements, the Pratt Hill quartzite is geochemically distinct from the rhyolites in the Fort Sill area, including the Davidson metarhyolite, with which some previous workers have grouped it, as discussed in Chapters 4 and 5. The Pratt Hill quartzite has a significantly higher silica content (79.39 wt %), which is due to its original siliciclastic composition, possibly along with some secondary silicification. The high Al₂O₃ content in the Pratt Hill quartzite is consistent with the presence of andalusite and may have been derived from detrital clay in the unit, but is also probably at least partly due to loss of alkalis during alteration. Although trace element geochemistry of the Pratt Hill quartzite will not be discussed in detail here, it has relatively low Ba and high Zr contents compared to the rhyolites in the Fort Sill area (Table 2). Low Ba contents may reflect the absence of alkali feldspar grains, and high Zr contents are likely due to the presence of detrital zircon.

Major element data for all the Wichita province felsic rocks shown in the Harker diagrams generally follow similar trends, suggesting comparable petrogenetic histories. In general, all of the samples show low CaO and MgO contents and high Fe/MgO ratios, which are
Figure 57. Igneous spectrum diagram of Hughes (1972).
characteristic features of A-type felsic rocks (e.g., Whalen et al., 1987; Eby, 1990). In detail, however, the Fort Sill rhyolite and Davidson metarhyolite generally show more evolved compositions than the other Wichita province felsic rocks in the Harker diagrams. The rhyolite dikes and xenoliths have similar major element contents to each other and plot near the data for the Davidson metarhyolite and Fort Sill rhyolite. This result may possibly mean that the rhyolite xenoliths came from similar extrusive units. However, the rhyolite dikes were emplaced late in the magmatic development of the Southern Oklahoma aulacogen and intrude the Mount Scott Granite. As such, it is unlikely that the rhyolite dikes are related to the rhyolites in the Fort Sill area. Samples for the Slick Hills rhyolites overall show less evolved compositions, with silica values ranging from 70.13 to 75.67 wt % and generally higher TiO$_2$, FeO, MgO, and P$_2$O$_5$ contents. The two hypabyssal rhyolite intrusions consistently plot with samples for the Slick Hills rhyolites that show the least evolved compositions. Samples for the Wichita granites have silica contents ranging from 73.75 to 77.00 wt%, and show major element trends in the Harker diagrams that are spread between the two fields occupied by rhyolites in the Slicks Hills and the Fort Sill area, but do not overlap with some of the less evolved Slick Hills rhyolites. Closer overlap of the granites with rhyolites in the Fort Sill area suggests they may be more closely related petrogenetically.

**Trace Elements**

**Rock Classification**

Due to the evidence for extensive alteration, classification of rock types based on major element contents is problematic. The samples are therefore plotted on the discrimination diagram of Winchester and Floyd (1977) in Figure 58. This diagram utilizes ratios of immobile elements
Figure 58. Discrimination diagram of Winchester and Floyd (1977).
that are unlikely to be modified by secondary alteration and thus provides the best indication of original rock compositions. Data for the Fort Sill rhyolite straddle the boundary between fields for normal and peralkaline rhyolites in the diagram, with most samples falling within the peralkaline field. The Davidson metarhyolite samples cluster with the Fort Sill rhyolite data and fall entirely in the peralkaline field. This result correlates with the more evolved major element compositions of both flows. The two hypabyssal rhyolite intrusions plot within the normal rhyolite field, close to the boundary with the trachyandesite field, consistent with the less evolved major element compositions of the intrusions. Note their nearly identical position on the diagram, indicating that they probably represent a single magma batch. Data for the Slick Hills rhyolites are spread between the fields for normal rhyolite, peralkaline rhyolite, and trachyandesite, with most of the samples clustering near the boundary separating the three fields. This correlates with their less evolved major element compositions, which is further indicated by several samples plotting entirely within the trachyandesite field. Although there is spread in the data, taken as a whole the Wichita province felsic rocks cluster in a relatively narrow range.

**Bivariate Plots of Immobile Trace Elements**

In representative bivariate plots of immobile trace elements and element ratios, samples from the Fort Sill rhyolite and Davidson metarhyolite consistently occupy two distinct groups (Figs. 59 to 63). The two hypabyssal rhyolite intrusions plot very close to each other in these figures, consistent with results from Figure 58. Note that the range in data for the Fort Sill rhyolite on the diagrams provides further evidence that this flow has significant primary compositional heterogeneities. The hypabyssal rhyolite intrusions plot with or relatively close to the Fort Sill rhyolite in Figures 59, 60, and 61. This raises the possibility that the intrusions may be petrogenetically linked to the Fort Sill rhyolite, in spite of their less evolved major element
Figure 59. Plot of Y versus Nb.

Figure 60. Plot of Th versus Nb.
Figure 61. Plot of Zr versus Nb.

Figure 62. Plot of TiO$_2$ versus Nb. Geochemical groups for rhyolites in the Wichita Mountains recognized by Hanson et al. (2014) are outlined in this and the following two diagrams.
compositions. However, this interpretation conflicts with Figures 62 and 63, where the rhyolite intrusions plot away from the Fort Sill rhyolite, indicating they were probably derived from separate magma sources. This result shows that multiple diagrams are necessary to determine such petrogenetic links.

Data for the Slick Hills rhyolites consistently plot separately from the Fort Sill rhyolite in Figures 59 to 64, showing overall higher concentrations of Nb, Th, and TiO$_2$, and generally higher Ti/Zr ratios, indicating that they were derived from a different source or magma reservoir than the Fort Sill rhyolite. In contrast, the Davidson metarhyolite plots with some of the samples from the Slick Hills rhyolites in Figures 59, 61, 62, and 63, pointing to a common source for those units.

Figures 62 to 64 show three separate geochemical groups of rhyolites in the Wichita Mountains that were identified by Hanson et al. (2014). The Fort Sill rhyolite defines Group 1. The Davidson metarhyolite plots with some rhyolites analyzed from the Slicks Hills, defining Group 2. Group 3 is defined by additional samples of rhyolites in the Slick Hills. As in the Fort Sill area, different rhyolite flows exposed in the same field area in the Slick Hills plot in separate groups [e.g., some rhyolite flows in the Bally Mountain area plot in Group 2, while others flows in the same area plot in Group 3 (Hanson et al., 2014)]. These data were interpreted by Hanson et al. (2014) as indicating that rhyolite flows in the Wichita Mountains were derived from a total of three separate magma reservoirs or sources. The data may also indicate a complex magma plumbing system at deeper levels, with rhyolite flows vertically stacked in the same field area that tapped different magma reservoirs. Isotopic data for the three groups are needed to test these interpretations (Hanson et al., 2014).
Figure 63. Plot of TiO$_2$ versus Zr/Nb.

Figure 64. Plot of Ta/Th versus Ti/Zr.
Normalized Multi-Element and REE Diagrams

Samples for Wichita province felsic rocks are plotted on a multi-element diagram normalized to primitive mantle in Figure 65. For clarity, samples from the Fort Sill area only are shown in Figure 65A, and those samples are plotted along with data from the Slick Hills rhyolites and Wichita granites in Figure 65B for comparison. Some of the variation in mobile elements in these diagrams can be attributed to secondary alteration.

Rhyolites in the Fort Sill area generally have similar patterns in Figure 65A. They show obvious depletions in Sr, P, and Ti. Depletion in Sr records fractionation of plagioclase and depletions in Ti and P indicate fractionation of titanomagnetite and apatite, respectively. The Fort Sill rhyolite and Davidson metarhyolite show slight depletions in Eu, which also indicates plagioclase fractionation. The two hypabyssal rhyolite intrusions show less depletion in Sr, P, and Ti than the Davidson metarhyolite and Fort Sill rhyolite, consistent with the less evolved compositions of the intrusions. The intrusions also have virtually identical patterns to each other, providing further evidence that they represent a single magma batch. Most of the samples from the Fort Sill area show slight Ba enrichment, which indicates some alkali feldspar accumulation in the magmas.

Samples of the Slick Hills rhyolites and Wichita granites show similar patterns to rhyolites in the Fort Sill area, with depletions in Sr, P, and Ti. In contrast, however, several samples from both suites show Ba depletion, particularly two samples of Wichita granites, indicating alkali feldspar fractionation. Most of the Wichita province felsic samples show slight negative Nb-Ta anomalies when compared to the nearest elements resistant to alteration (Th and La), suggesting some involvement of older, subduction-modified lithosphere in the petrogenesis of the magmas (e.g., Pearce, 1982).
Figure 65. (A) Multi-element diagram for rhyolites in the Fort Sill area. (B) Multi-element diagram for Wichita province felsic rocks. Normalization values in both diagrams are from Sun and McDonough (1989). Mobile elements are circled on the x-axis.
Because rare-earth-elements (REE) are mostly resistant to secondary alteration (Hanson, 1980; Rollinson, 1993), they are particularly useful for comparing petrogenetic relations within a given suite of rocks. REE patterns for rhyolites in the Fort Sill area are shown in Figure 66A, and for comparison those data together with Slick Hills rhyolite and Wichita granite samples are shown in Figure 66B. Complete REE data are available for five samples of the Fort Sill rhyolite, which show LREE enrichment and negative Eu anomalies (Fig. 66A), consistent with fractionation of plagioclase. Four of the samples have very similar overall REE patterns, but the other sample shows lower LREE contents, which fits with other evidence for compositional heterogeneities in the Fort Sill rhyolite. A single sample of Davidson metarhyolite from Price (1998) shows a somewhat comparable pattern to the Fort Sill rhyolite sample with the lower LREE contents, with irregularities that may reflect mobilization of some of the REE in the highly altered Davidson metarhyolite. Overall, the other Wichita province felsic rocks show similar REE patterns, with some samples of Wichita granites showing stronger negative Eu anomalies (Fig. 66B).

**Tectonic Discrimination Diagrams**

Data for Wichita province felsic rocks are plotted on standard discrimination diagrams utilizing immobile trace elements in Figures 67 and 68. In the diagram from Pearce et al. (1984), data from the Fort Sill area cluster tightly together in the within-plate granite field (Fig. 67). There is slightly more spread in the diagram of Whalen et al. (1987), with the Davidson metarhyolite separated from the Fort Sill rhyolite and hypabyssal rhyolite intrusions (Fig. 68). However, all of the data plot well within the A-type granite field in that diagram. Data for the Wichita granites and Slick Hills rhyolites cluster in the same areas on these diagrams as data for
Figure 66. (A) REE diagram for the Davidson metarhyolite and Fort Sill rhyolite. (B) REE diagram for Wichita province felsic rocks. Normalization values in both diagrams are from Sun and McDonough (1989).
Figure 67. Nb versus Y discrimination diagram of Pearce et al. (1984).

Figure 68. Zr versus $10^4$Ga/Al discrimination diagram of Whalen et al. (1987).
rhyolites in the Fort Sill area, emphasizing the within-plate, A-type affinities of all Wichita province felsic rocks.

In Figure 69, data for Wichita province felsic rocks plot close to the boundary between the A_1 and A_2 fields recognized by Eby (1992) for different categories of A-type felsic rocks. The A_1 field represents felsic rocks that have ocean-island basalt (OIB)-type sources and are generated either from hotspot activity or during intracontinental rifting. A_2 type felsic rocks characteristically come from sources previously modified by arc magmatism. Note that a majority of the Fort Sill rhyolite samples, the two hypabyssal rhyolite intrusions, and two samples of the Davidson metarhyolite plot in the A_2 field, indicating that lithosphere modified by arc magmatism played a role in the petrogenesis of those magmas. This result is consistent with the negative Nb-Ta anomalies in Figure 65, and is emphasized in Figure 70, where the samples partly plot in the field for OIB but spread toward values for average crust and collisional granites derived from crustal anatexis; the Fort Sill rhyolite shows the greatest overall spread in the data on this diagram. Data for the Wichita granites and Slick Hills rhyolites also plot close to the boundary for the A_1 and A_2 fields in Figure 69. However, the data for these units spread slightly more towards the A_1 field, suggesting the petrogenesis of those magmas was less influenced by lithosphere modified by arc magmatism. This is further illustrated in Figure 70, where samples for the Wichita granites and Slick Hills rhyolites plot in or near the OIB field with less spread towards values for average crust and collisional granites compared to the Fort Sill rhyolite.
Figure 69. (A) Y-Nb-Ga discrimination diagram of Eby (1992) for A-type felsic rocks. (B) Y-Nb-Ce discrimination diagram of Eby (1992) for A-type felsic rocks.
Figure 70. Ce/Nb versus Y/Nb diagram of Eby (1990) for A-type felsic rocks. 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.
CHAPTER 8: CONCLUSIONS

Overview

The Carlton Rhyolite Group and related Wichita Granite Group represent a large volume of A-type felsic magma emplaced during Cambrian rifting in the Southern Oklahoma aulacogen. The rhyolites are exposed both in the Wichita and the Arbuckle Mountains, and are known from a much larger area in the subsurface. The largest rhyolite outcrops in the Wichita Mountains occur in and adjacent to the Fort Sill Military Reservation.

My mapping, together with previous work, indicates that two major, lithologically distinct rhyolite flows occur in the Fort Sill area, the Davidson metarhyolite and the overlying Fort Sill rhyolite. A discontinuous unit of volcaniclastic metasedimentary rocks separates the two flows. Both flows are intruded by the Mount Scott Granite, which forms a large, sheet-like intrusion in this part of the Wichita Mountains. Complex, interfingering contact relations occur in places where granite has intruded between the Davidson metarhyolite and Fort Sill rhyolite. Two fault zones, which I have termed the Little Medicine Creek Fault Zone and the Deer Creek Canyon Fault Zone, occur in the study area and have unknown amounts of displacement. The Little Medicine Creek Fault Zone offsets both the Davidson metarhyolite and Fort Sill rhyolite, whereas the Deer Creek Canyon Fault Zone affects only the Fort Sill rhyolite.

Davidson Metarhyolite

Outcrops of the Davidson metarhyolite were mapped as quartzite by some previous workers (Taylor, 1915; Gilbert, 1982b). Ham et al. (1964) and Price (1998) have interpreted most of these outcrops to represent contact-metamorphosed rhyolite, and I concur with this
interpretation. Features typical of rhyolite lavas are well displayed throughout the unit, although they have been variably modified by metamorphic recrystallization.

The Davidson metarhyolite can be traced discontinuously for ~9.25 km along strike but is truncated both to the east and west by intrusive granite. Only remnants of the metarhyolite are preserved and its original morphology and thickness are unknown. The unit is mostly aphyric, although in places it contains a few percent of altered alkali feldspar phenocrysts. In contrast to the Fort Sill rhyolite described below, the Davidson metarhyolite does not display a regular, vertical cooling zonation. Delicate flow lamination is present throughout the unit and is commonly deformed by complex flow folds. Flow breccia is locally well developed, and basaltic inclusions occur in places. Some exposures show crude columnar jointing.

In thin section, relict flow lamination is overprinted by recrystallization of the groundmass to a very fine grained, granoblastic intergrowth of quartz and altered alkali feldspar that has mostly been replaced by sericite, with variable amounts of metamorphic muscovite and biotite. The presence of sillimanite and andalusite suggests significant loss of alkalis during contact metamorphism, creating an alumina-oversaturated bulk composition. Some parts of the Davidson metarhyolite contain an unusually large amount of granoblastic quartz, indicating significant silicification also occurred. Thin magnetite and quartz veins cut parts of the unit and record two separate phases of fluid migration inferred to have occurred during contact metamorphism caused by intrusion of the Mount Scott Granite.

**Volcaniclastic Metasedimentary Rocks**

A discontinuous volcaniclastic metasedimentary unit that thins dramatically to the west was deposited on an irregular erosional surface that developed on top of the Davidson metarhyolite. Internal bedding and contacts with the overlying Fort Sill rhyolite indicate that the
metasedimentary rocks dip at shallow angles to the south. Part of the volcaniclastic unit has been termed the Pratt Hill quartzite where it is exposed at the base of Pratt Hill (Sides and Miller, 1982), and I have found stratigraphically equivalent metasedimentary rocks in two separate areas to the west, including outcrops in the Hide-A-Way area. The unit at Pratt Hill is $\geq 20$ m thick, consists mostly of granoblastic quartzite with rare andalusite crystals, and is capped by a $\sim 1$-m-thick, matrix-supported, polymict debris-flow deposit that is directly overlain by the Fort Sill rhyolite. The Pratt Hill quartzite thins to the west where it makes up the basal few meters of the volcaniclastic interval exposed in the Hide-A-Way area. There the quartzite is overlain by a $\sim 10.5$-m-thick sequence of rhyolitic tuffaceous metasandstones interbedded with a matrix-supported, polymict debris-flow deposit. West of the Hide-A-Way area the interval is only $\sim 1$ m thick and consists of planar bedded, rhyolitic tuffaceous metasandstone capped by thin metasiltstone.

The rhyolitic tuffaceous metasedimentary rocks are mostly coarse-grained sandstones containing monocrystalline quartz and alkali feldspar grains. This detritus could not have been derived from the nearly aphyric Davidson metarhyolite and must have come from rhyolites exposed elsewhere. The debris-flow deposits also contain angular porphyritic rhyolite clasts that are unlike the Davidson metarhyolite and record influx of volcanic debris from outside the Fort Sill area, suggesting a more complex, evolving volcanic field than has previously been recognized.

**Fort Sill Rhyolite**

Stratigraphically overlying the volcaniclastic rocks, and where they are absent, the Davidson metarhyolite, is the Fort Sill rhyolite. Outcrops of that unit cover up to $\sim 30$ km$^2$ and form the largest rhyolite exposures in the Wichita Mountains. The Fort Sill rhyolite can be traced
~18.5 km along strike, making it the single longest rhyolite flow documented in the Carlton Rhyolite Group. The margins of the flow are truncated by intrusive granite or covered, so it could have originally been much larger. It has an eroded thickness >100 m and appears to have a broadly tabular shape.

The Fort Sill rhyolite contains abundant quartz and alkali feldspar phenocrysts and displays a vertical cooling zonation. At the base of the rhyolite exposed on Pratt Hill, local preservation of relict perlitic texture is visible in thin section, indicating the original presence of glass. West of Pratt Hill, peperite is locally developed at the base of the rhyolite, with fragments from the base of the flow mixed with rounded silt- and sand-sized quartz grains. Within coherent rhyolite immediately above the peperite, fractures filled with similar quartz grains also occur. These features record flowage of the lava over wet, unconsolidated sediment, causing fragmentation of the flow base while fluidized sediment was injected upward into fractures in quenched rhyolite.

Immediately above the originally glassy base of the Fort Sill rhyolite, a transition zone is defined by delicate flow lamination that is subparallel to the base of the flow, with rare amygdules and common fine-scale snowflake texture visible in thin section. This transition zone grades rapidly into the homogenous flow interior. The majority of outcrops of the Fort Sill rhyolite appear to represent the interior of the flow, which is mostly characterized by unbanded rhyolite with felsitic groundmass texture in hand sample. In places, however, the interior of the flow displays a well-defined flow banding with pink flow bands contained within dark-gray rhyolite that has felsitic and snowflake textures in thin section. The pink flow bands have a relatively coarse grained, partly spherulitic texture with crystals of tridymite (now inverted to quartz) intergrown with feldspar. The pink bands are laterally discontinuous and have flame-like
Discordant features with identical textures extend from some of the pink bands and transgress across the adjacent dark-gray rhyolite at high angles. Such features are inconsistent with flattened pumice described in welded ignimbrites. The coarser grain size in the pink bands is inferred to reflect higher dissolved volatile concentrations in some layers, which increased crystal growth rates during devitrification.

Pseudohexagonal columnar jointing is visible in places in the flow interior (e.g., Medicine Bluffs) and is approximately perpendicular to the base of the flow, consistent with uniform cooling after the flow came to rest. In some areas, the flow banding is much better developed than usual and is deformed by flow folds. The flow bands consist of felsitic rhyolite alternating with dark green, originally glassy rhyolite. Flow lineation and pockets of flow breccia are also present. Based on the presence of these features, including the abundance of glass, I infer that the outcrops in these areas are close to the original upper margin of the flow.

Extensive extrusive units of this type have been documented from a number of A-type volcanic provinces and have been explained in two ways. Many workers argue that at least some of these laterally extensive units are true lava flows emplaced non-explosively; relatively low viscosities of the A-type magmas coupled with high effusion rates are thought to explain the ability of the lavas to flow significant distances from source vents (e.g., Twist and French, 1983; Henry et al., 1990; Henry and Wolf, 1992; Green and Fitz, 1993; Allen and McPhie, 2002). An alternate possibility is that such units represent rheomorphic ignimbrites formed from explosive eruption and transport as pyroclastic flows, which underwent welding and homogenization during and/or after emplacement, with nearly complete elimination of original pyroclastic textures (Branney and Kokelaar, 1992). Rheomorphic ignimbrites typically preserve pyroclastic textures near the base of the deposit (Henry and Wolff, 1992). Such features are lacking in the
Fort Sill rhyolite. I infer that this unit represents a remnant of a voluminous lava flow erupted in a nonexplosive manner, comparable to examples documented from other A-type felsic volcanic provinces. The flow was emplaced as a single, thick cooling unit, permitting development of subvertical cooling joints in the flow interior and coarse devitrification textures concentrated in flow bands. Peperite preserved at the base of the unit provides evidence for flow of lava over wet, unconsolidated sediment.

The vertical cooling zonation in the Fort Sill rhyolite differs in two main respects with the zonation documented in other flows of Carlton Rhyolite exposed in the Slick Hills to the north and discussed in Chapter 2. One obvious difference is that Carlton Rhyolite flows in the Slick Hills commonly have well-defined lithophysal zones in the inner parts of the glassy chilled margins, whereas lithophysae are absent in the Fort Sill rhyolite. This may indicate lower volatile concentrations in the magma that formed the Fort Sill rhyolite or the loss of volatiles during eruption. Secondly, flow interiors in the Slick Hills are characterized by homogenous felsitic rhyolite that lacks flow banding and has randomly oriented to radiating tridymite needles that increase in size progressively towards the flow centers. This is in marked contrast to the discontinuous flow banding with flame-like terminations in the interior of the Fort Sill rhyolite. The origin of this discontinuous flow banding is unclear, but it may have been caused by higher emplacement rates and greater degrees of shear strain, with volatiles migrating to shear planes spaced throughout much of the flow interior.

**Rhyolite and Diabase Intrusions**

Two small hypabyssal rhyolite intrusions cut the Fort Sill rhyolite in different areas. They contain abundant, randomly oriented tridymite needles (now inverted to quartz) that are longer
than those in the Fort Sill rhyolite, and interstitial microgranophyre is present between the
needles. Unlike the Fort Sill rhyolite, the intrusions contain rounded basaltic inclusions.

Diabase intrusions in the Fort Sill area generally form small dikes. In addition to those
previously reported by other workers, I mapped two diabase dikes cutting the Fort Sill rhyolite
on Jones Ridge and another near the base of Heyls Hill. The diabase dike at Heyls Hill trends
northwest, roughly parallel to the structural grain of the Southern Oklahoma aulacogen, and
exhibits subophitic texture in thin section defined by plagioclase laths that are partially enclosed
by clinopyroxene crystals.

**Geochemistry**

Rhyolites in the Fort Sill area, along with other Wichita province felsic rocks, share
compositional similarities to rocks from other A-type felsic provinces (e.g., Eby, 1990; Menuge
et al., 2002; Tollo et al., 2004). These similarities include high Nb, Zr, Ta, Ga, Y, and REE
(except Eu) contents, high Fe/Mg ratios, high K$_2$O+Na$_2$O, and relatively low concentrations of
CaO, Al$_2$O$_3$, Sr, and Eu. On standard discrimination diagrams using immobile trace elements
(Pearce et al., 1984; Whalen et al., 1987), data for rhyolites in the Fort Sill area cluster tightly in
within-plate, A-type fields, and the majority of them fall in the peralkaline field on the diagram
of Winchester and Floyd (1977). Common secondary fluorite in thin sections from the Fort Sill
rhyolite suggests relatively high original contents of magmatic F, which is another characteristic
feature of A-type felsic rocks (Loiselle and Wones, 1979; Whalen et al., 1987; Eby, 1990).

Major element trends for the Fort Sill rhyolite, Davidson metarhyolite, and hypabyssal
rhyolite intrusions on Harker variation diagrams show decreasing CaO, MgO, FeO, TiO$_2$, and
P$_2$O$_5$ with increasing SiO$_2$, which could result from fractional crystallization in crustal magma
chambers or progressive partial melting of source rocks at deeper levels. The Fort Sill rhyolite
shows a significant range in major element data that is interpreted to reflect primary compositional differences, indicating that the unit represents a chemically heterogeneous batch of magma. A wide range in immobile trace elements such as Zr, Nb, Th, and Y in this unit also supports this interpretation. The two hypabyssal rhyolite intrusions have significantly less evolved major element compositions than the Fort Sill rhyolite and Davidson metarhyolite. The latter two units show broad similarities in major element compositions, although the Davidson metarhyolite has higher Al₂O₃ contents likely due to alkali loss during contact metamorphism. The Pratt Hill quartzite is geochemically distinct from the rhyolites in the Fort Sill area, consistent with its sedimentary origin.

The Fort Sill rhyolite and Davidson metarhyolite show the most evolved major-element compositions of all the rhyolites exposed in the Wichita Mountains, with higher SiO₂ and lower TiO₂, FeO, MgO, and P₂O₅. Na₂O and K₂O do not show well-defined trends in the rhyolites in the Fort Sill area or in any of the other Wichita province felsic rocks, which indicates that alkali mobilization was probably common during alteration of felsic rocks throughout the province.

On normalized multi-element and REE diagrams, rhyolites in the Fort Sill area have similar trends to the Wichita granites and Slick Hills rhyolites, indicating similar petrogenetic histories. All of these rocks show depletions in Ti, P, and Sr, consistent with fractionation of titanomagnetite, apatite, and plagioclase. REE patterns show LREE enrichment and negative Eu anomalies, again consistent with fractionation of plagioclase. Rhyolites in the Fort Sill area show slight Ba enrichment, indicating alkali feldspar accumulation, while some of the Wichita granites and Slick Hills rhyolites show depletion in Ba, signifying alkali feldspar fractionation in those magmas.
On bivariate plots utilizing immobile trace elements and element ratios, the Fort Sill rhyolite, Davidson metarhyolite, and hypabyssal rhyolite intrusions each typically cluster in separate areas. Rhyolite samples from the Slick Hills also cluster in two separate groups (Hanson et al., 2014), one of which overlaps with data for the Davidson metarhyolite. These results indicate that rhyolite flows in the same outcrop area in some cases tapped different magma source regions or reservoirs.

In trace-element diagrams developed by Eby (1990, 1992) that constrain different sources for A-type felsic rocks, rhyolites in the Fort Sill area show evidence for derivation partly from an OIB-type source, but with variable degrees of involvement of older lithosphere modified by arc magmatism. Other Wichita province felsic rocks show similar results, indicating that subduction-modified lithosphere played a role in the petrogenesis of many of the felsic magmas.
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ABSTRACT

PHYSICAL VOLCANOLOGY AND GEOCHEMISTRY OF THE CAMBRIAN CARLTON RHYOLITE IN THE FORT SILL AREA, SOUTHWESTERN OKLAHOMA

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The Carlton Rhyolite Group was emplaced during Cambrian rifting within the Southern Oklahoma aulacogen. Outcrops occur in the Wichita and Arbuckle Mountains. The largest exposures are in the Fort Sill area in the Wichita Mountains where two rhyolite flows are present. The mostly aphyric Davidson metarhyolite can be traced ~9.25 km along strike. The overlying Fort Sill rhyolite is rich in quartz and alkali feldspar phenocrysts and is the longest flow documented in the Carlton Rhyolite Group. It can be traced ~18.5 km along strike and is inferred to be a remnant of an originally more extensive lava flow, comparable to extrusive units documented from other A-type felsic provinces. A discontinuous unit of volcaniclastic metasedimentary rocks separates the two flows and their margins are partly truncated by intrusive granite. Geochemical data indicate both flows have within-plate, A-type compositions and were derived from separate magma reservoirs or sources.