An Overview of the Carlton Rhyolite Group: Cambrian A-type felsic volcanism in the Southern Oklahoma Aulacogen

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GEOLOGIC SETTING

Cambrian igneous rocks of the Southern Oklahoma Aulacogen are widespread in the subsurface of southern Oklahoma and adjacent parts of Texas (Fig. 1). Their extent was first documented in detail in the pioneering work of Ham et al. (1964). Those workers introduced the term Wichita Province to refer both to the igneous rocks and the Tillman Metasedimentary Group, which occurs in the subsurface partly in the same area, and which Ham et al. (1964) believed records the initial formation of a major basin tectonically linked to the igneous activity. More recent work suggests that the Tillman Metasedimentary Group represents an older, Proterozoic episode of sedimentation unrelated to the Cambrian magmatism (Brewer et al., 1981; Van Schmus et al., 1993), and here we use the term Wichita Igneous Province to focus specifically on the igneous rocks emplaced during development of the Southern Oklahoma Aulacogen. Part of the Precambrian basement assemblage that the aulacogen cuts across is exposed in the eastern Arbuckle Mountains (Fig. 2). Ham et al. (1964) assigned these rocks to the Eastern Arbuckle Province in order to differentiate them from the younger Wichita Province, but on a larger scale they represent part of the ~1.4 Ga Southern Granite-Rhyolite Province that extends over considerable areas in the subsurface in this part of the Midcontinent (Van Schmus et al., 1996; Rohs and Van Schmus, 2007).

Development of the Wichita Igneous Province was directly linked to opening of the southern part of the Iapetus Ocean along this part of the Laurentian margin. Hoffman et al. (1974) interpreted the magmatism to have occurred within the failed arm of a rift-rift-rift triple junction. In their model, rifting along the other two arms gave way to seafloor spreading and continental breakup, while thermal subsidence following cessation of igneous activity in the failed arm led to deposition of a thick, mostly marine lower Paleozoic sedimentary succession centered on the area previously occupied by the magmatically active rift zone. Thomas (1991, 2011, and this guidebook) has argued against this interpretation and has instead proposed that the magmatism was associated with a leaky transform boundary developed along an offset in the continental margin established during initial stages in rifting.

Inversion of the Southern Oklahoma Aulacogen resulted in uplift of parts of the Cambrian igneous assemblage in major compressional or transpressional structures while other parts were downwarped in linked basins (McConnell, 1989; Perry, 1989), the largest and deepest of which is the Anadarko Basin (Fig. 1). This deformation occurred primarily in the Pennsylvanian, with limited tectonism extending into the Early Permian (Ye et al., 1996), and is inferred to have been related to collisional orogenesis in the Ouachita fold-and-thrust belt along the southern Laurentian margin or to more distance events along the Cordilleran margin to the west (e.g., Granath, 1989; Ye et al., 1996).

Surface exposures of the Wichita Igneous Province are strongly bimodal, although recent work by Brueseke et al. (this guidebook) indicates that rocks with intermediate compositions occur in larger amounts in the subsurface than in the available outcrops. The most extensive igneous outcrops occur in the Wichita Mountains (Fig. 3) from which the province takes it name. Gabbroic rocks exposed there belong to the Raggedy Mountain Gabbro Group (Ham et al., 1964), which consists of a large tholeiitic layered intrusion termed the Glen Mountains Layered Complex (Powell et al., 1980; Cooper, 1991) and a series of smaller tholeiitic gabbro plutons that intrude the layered complex and are compositionally unrelated to it; these younger intrusions are termed the Roosevelt Gabbro (Powell et al., 1980; Powell, 1986). Ham et al. (1964) interpreted the Raggedy Mountain Gabbro Group to be the intrusive equivalent of the Navajoe Mountain Basalt-Spilite Group, a unit of altered basaltic

Figure 1. Southern Oklahoma Aulacogen in relation to early Paleozoic continental margin of North America. Extent of Wichita Igneous Province in the subsurface is shown by red and orange colors; approximate areas where these rocks crop out are outlined. Modified from Hanson et al. (2013); faults from Thomas (1991) and Northcutt and Campbell (1998); early Paleozoic continental margin from Keller and Stephenson (2007). A: location of subsurface Carlton Rhyolite outlier near Altus, Oklahoma; MVF: Mountain View Fault; WVF: Washita Valley Fault.

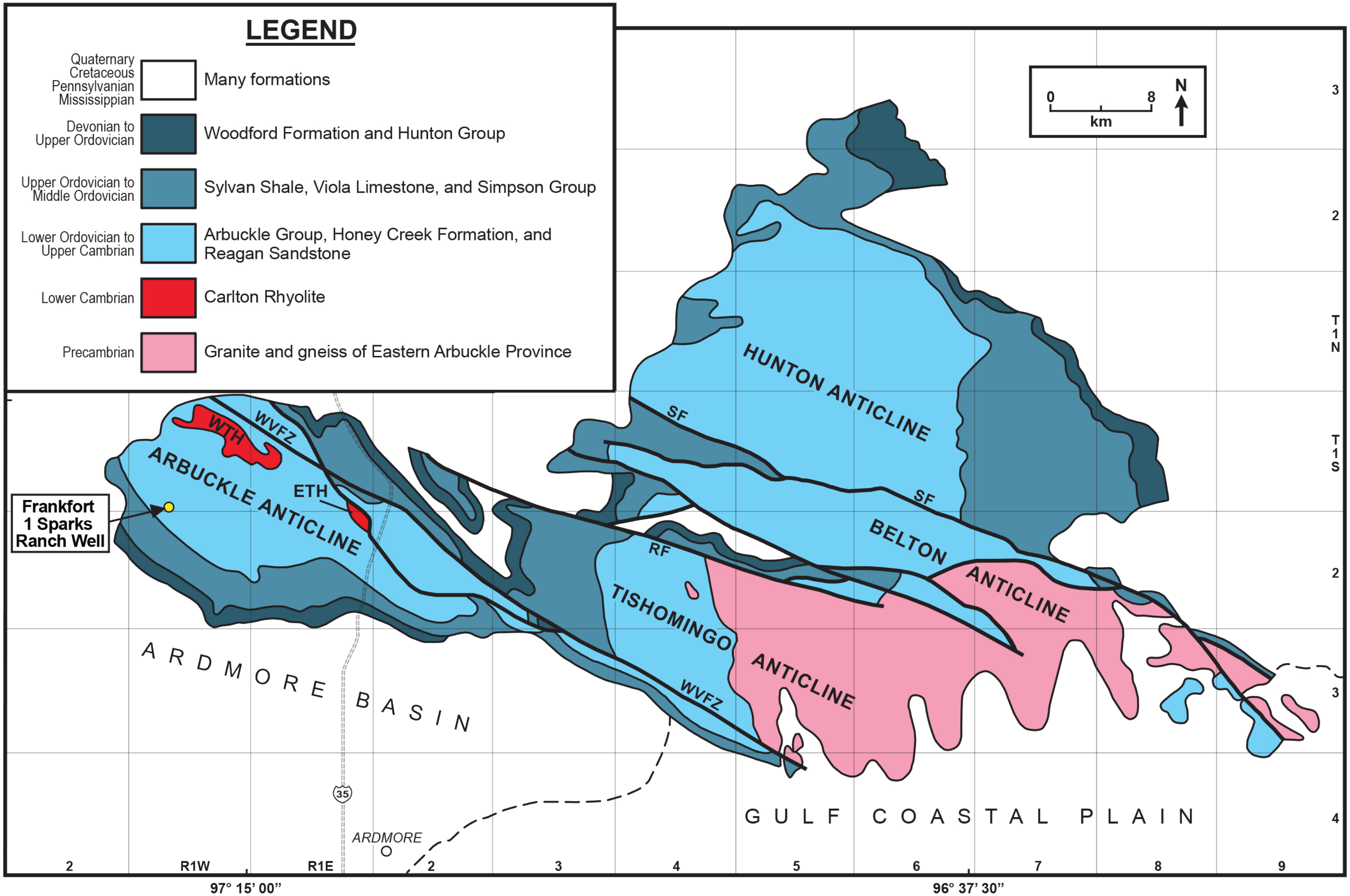

Figure 2. Geologic map of the Arbuckle Mountains, modified from Ham (1973). Location of Frankfort 1 Sparks Ranch well is indicated. WTH: West Timbered Hills; ETH: East Timbered Hills; WVFZ: Washita Valley Fault Zone; RF: Reagan Fault; SF: Sulphur Fault.

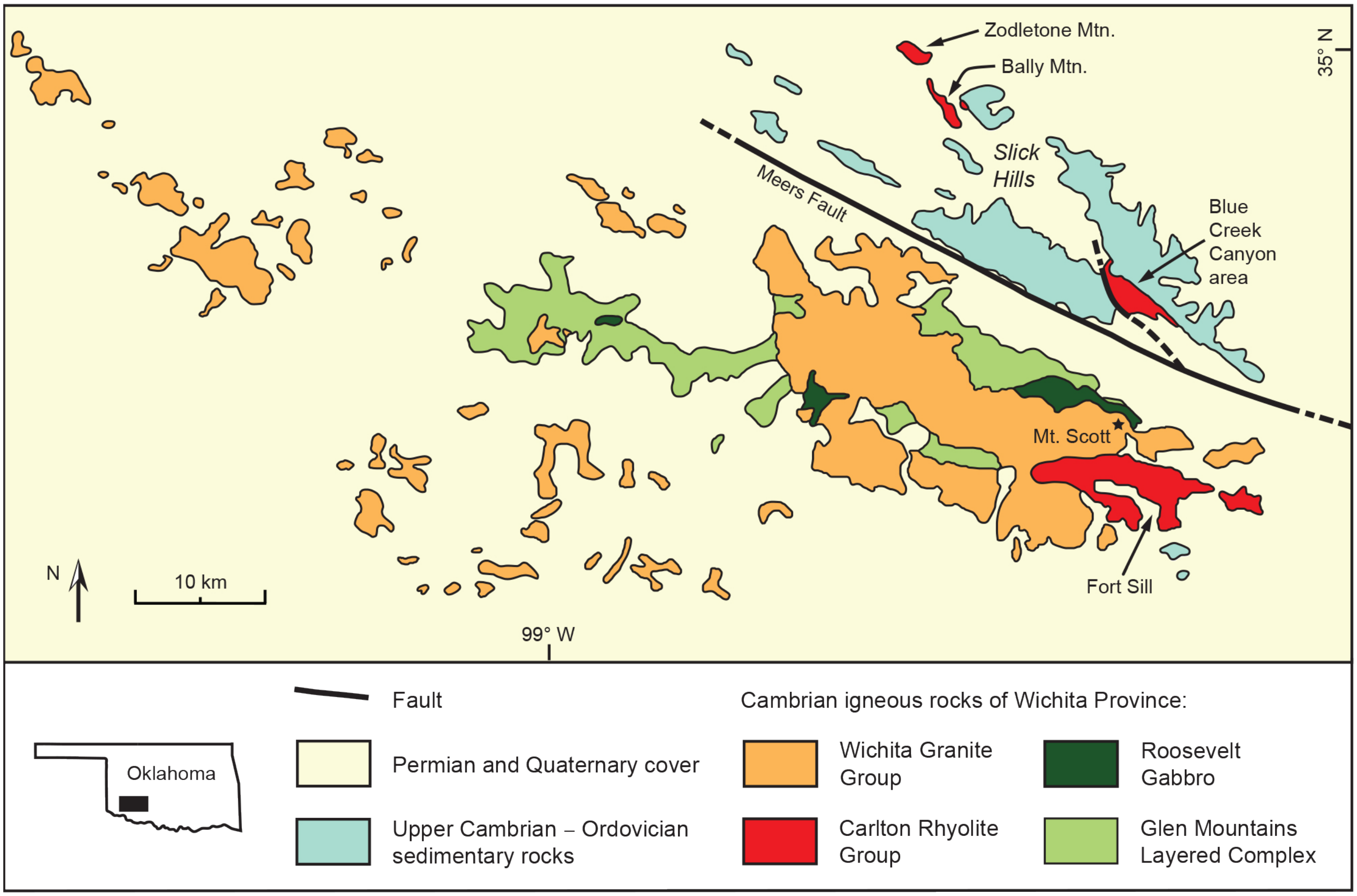

Figure 3. Simplified geological map of the Wichita Mountains, modified from Powell et al. (1980) and Donovan (1995).

to andesitic volcanic rocks present in the subsurface in the western parts of the Wichita Igneous Province. More specifically, Gilbert (1983) argued that the basaltic rocks were extruded during the same magmatic episode that formed the Glen Mountains Layered Complex. At the time Ham et al. (1964) published their work, the basaltic rocks had been penetrated by 11 wells. The maximum thickness drilled was 320 m, and the stratigraphic base of the unit was not reached. Direct evidence bearing on the timing relations between the Navajoe Mountain Basalt-Spilite Group and the intrusive gabbros is lacking, and the inference that the basaltic rocks and at least some of the gabbros are directly related remains unproven.

The Glen Mountains Layered Complex underwent a major episode of tilting, uplift, and erosion prior to widespread emplacement of rhyolites and granites (Powell and Phelps, 1977; Gilbert, 1983), and McConnell and Gilbert (1990) have interpreted the tilting to record an early episode of extensional block faulting within the developing rift. The rhyolites crop out both in the Wichita Mountains and in the Arbuckle Mountains ~100 km farther to the east (Figs. 1, 2, and 3), and Denison (1958) and Ham et al. (1964) showed that the two outcrop areas are connected by an apparently continuous rhyolite succession in the subsurface. Ham et al. (1964) introduced the term Carlton Rhyolite Group for all the Cambrian rhyolitic volcanic rocks present in southern Oklahoma, and they referred to the associated granites as the Wichita Granite Group. In the area of the Wichita Mountains, the rhyolites were extruded onto the erosional surface carved into the tilted Glen Mountains Layered Complex (Ham et al., 1964; Gilbert, 1983; Gilbert and Denison, 1993). In adjacent areas in the subsurface the rhyolites are underlain in places by the Navajoe Mountain Basalt-Spilite Group (Ham et al., 1964).

Much of the Wichita Granite Group was intruded as a series of sheet-like bodies between the older mafic rocks and the rhyolites in what has been described as a crustal magma trap created when the rhyolitic volcanic pile became thick enough to impede the rise of subsequent pulses of felsic magma (Hogan and Gilbert, 1995; Hogan et al., 1998). The most extensive sheet-like intrusion is the Mount Scott Granite. This body can be traced laterally for as much as 55 km but has a preserved thickness of only 500 m, which is probably close to its original thickness (Price, this guidebook). Both the rhyolites and granites have A-type affinities as indicated by geochemical data summarized below and by evidence for high magmatic temperatures, high fluorine contents in the magmas, and relatively low initial H_2O contents (Myers et al., 1981; Hogan and Gilbert, 1997, 1998; Price et al., 1999). Zr geothermometry indicates temperatures as high as 950º C for the rhyolite magmas (Hogan and Gilbert, 1997).

Numerous diabase dikes, sills, and transgressive sheets intrude the granites and rhyolites as well as the mafic plutonic rocks (e.g., Ham et al., 1964; Hogan and Gilbert, 1998). The diabases typically have tholeiitic to transitional compositions (Cameron et al., 1986; Aquilar, 1988; DeGroat et al., 1995; Eschberger et al., paper, this guidebook), and many of the dikes have northwest trends parallel to the axis of the aulacogen (Denison, 1995). Similar diabase dikes intrude Mesoproterozoic crystalline rocks exposed in the eastern Arbuckle Mountains, northeast of the northern margin of the aulacogen (Fig. 2), where they have been termed the Mill Creek swarm (Lidiak et al., paper, this guidebook). The dikes increase in abundance as the aulacogen margin is approached (Denison, 1995) and locally make up ≥30% of the total exposed rock volume. Some of these dikes may be Proterozoic in age (Denison, 1995; Lidiak et al., paper, this guidebook), but most are considered to have been emplaced during Cambrian rifting. Diabase intrusions typically occur in much smaller amounts in exposures of the Carlton Rhyolite in the western Arbuckle Mountains, across the aulacogen boundary. These field relations suggest that much of the Mill Creek dike swarm in the eastern Arbuckles records an episode of rift-related magmatism that preceded emplacement of the felsic rocks (Denison, 1995).

Geophysical data show that those parts of the Wichita Igneous Province exposed at the surface or penetrated by drilling represent only the upper part of an enormous mass of igneous rock that extends down to mid-crustal levels along the trend of the Southern Oklahoma Aulacogen (Keller and Stephenson, 2007; Buckey, this guidebook). Seismic studies indicate a mafic composition for this igneous mass (Keller and Stephenson, 2007), and it may consist of both basaltic lavas and layered mafic complexes comparable to the Glen Mountains Layered Complex exposed in the Wichita Mountains. The total volume of these mafic rocks is ~210,000 km^3 (Hanson et al., 2013).

Modern isotopic age constraints are available for parts of the Wichita Igneous Province, but many of the results have been published only in abstracts. The Glen Mountains Layered Complex has yielded a Sm-Nd isochron date of 528 ± 29 Ma (Lambert et al., 1988) although the relatively large error bar on this result makes it difficult to place within a detailed temporal model for evolution of the aulacogen. Wright et al. (1996) and Degeller et al. (1996) reported U-Pb zircon isotopic dates ranging from 535 ± 3 to 530 ± 1 Ma for some of the Wichita granites and for a rhyolite xenolith contained in granite. Hanson et al. (2009) reported preliminary U-Pb zircon dates of ~532 Ma from two rhyolite flows at Bally Mountain north of the main mass of the Wichita Mountains (Hanson et al., this guidebook). The only fully published U-Pb zircon geochronological results for the Wichita felsic rocks come from Thomas et al. (2012) who obtained U-Pb zircon dates of 539 ± 5 Ma for rhyolite in the western Arbuckle Mountains and 536 ± 5 Ma for a rhyolite dike intruding Mesoproterozoic basement farther east. The zircon age results as a whole are consistent with emplacement of the felsic igneous rocks in a limited time frame in the Early Cambrian. One of the Roosevelt gabbros that intrudes the Glen Mountains Layered Complex and is in intrusive contact with the overlying Mount Scott Granite has yielded $^{40}Ar/^{39}Ar$ hornblende and biotite dates of 533 ± 2 and 533 ± 4 Ma, respectively (Hames et al., 1998). These results overlap zircon ages for the Wichita granites and are consistent with field evidence that some of the Roosevelt gabbros were emplaced at about the same time as the granites (Price et al., 1998a; Gilbert and Hogan, 2010). However, the $^{40}Ar/^{39}Ar$ results conflict with a U-Pb zircon date for the same gabbro of 552 ± 7 Ma (Bowring and Hoppe, 1982), and additional work is needed to resolve this discrepancy. The present geochronological database does not provide tight constraints on the older igneous rocks of the province, and it is possible that some of the early magmatism occurred in the late Neoproterozoic.

EXTENT AND STRATIGRAPHIC RELATIONS OF THE CARLTON RHYOLITE GROUP

Rhyolite exposures in the Wichita Mountains are largely restricted to the eastern part of that range where they occur in the Slick Hills and the Fort Sill area (Fig. 3). In the Arbuckle Mountains, the rhyolites crop out in the East and

West Timbered Hills south of the Washita Valley Fault Zone (Fig. 2). Lower Paleozoic sedimentary strata of the Timbered Hills and Arbuckle Groups rest unconformably on the rhyolites in both the Wichita and Arbuckle Mountains and record a major marine transgression across the region after Early Cambrian igneous activity ceased. Lower parts of the transgressive sequence comprise the Upper Cambrian Reagan Sandstone and Honey Creek Formation in the Timbered Hills Group. Basal parts of the Reagan Sandstone were deposited in fluvial environments, but these strata are succeeded by shallow-marine clastic and carbonate rocks in the upper part of the Reagan and in the Honey Creek Formation. The overlying Arbuckle Group records development of an extensive Upper Cambrian-Lower Ordovician carbonate platform (Donovan, 1995; Johnson et al., 1988). There is evidence for a considerable amount of erosion along the unconformity at the base of the Reagan, and a number of rhyolite paleohills rising above the general surface of the unconformity have been documented in the Slick Hills (Donovan and Bucheit, 2000) and in the subsurface northwest of outcrops in the Arbuckle Mountains (Puckett et al., this guidebook). The largest paleohills in the Slick Hills extend as much as ~300 m above the general unconformity surface and are onlapped by lower Arbuckle Group strata (Donovan and Bucheit, 2000).

The subsurface extent of the Carlton Rhyolite Group is not precisely known because so much of the volcanic field is deeply buried beneath younger sedimentary rocks. The distribution of the rhyolites shown in Figure 1 south of the Mountain View and Washita Valley Faults is mostly from Denison (1958) and Ham et al. (1964) with modifications by Denison et al. (1984). The rhyolites are also likely to have originally covered much or all of the area in southwestern Oklahoma where intrusive Wichita igneous rocks now form the uppermost preserved parts of the igneous assemblage in outcrop and in the subsurface (Figs. 1 and 3). Rhyolite xenoliths as much as 50 m across are locally abundant in granite outcrops in this area (Hogan and Gilbert, 1997; Price et al., 1998b), and part of the original rhyolite cover that forms the roof to a Wichita granite sill is present in the subsurface near Altus (Fig. 1; Ham et al., 1964).

The distribution of the rhyolites in the Texas Panhandle is poorly constrained partly because of the difficulty in distinguishing subsurface samples of Carlton Rhyolite from Mesoproterozoic rhyolites of the Southern Granite-Rhyolite Province, which also occur in that region (Muehlberger et al., 1967; Van Schmus et al., 1996). The northern limit of the rhyolites in Oklahoma in Figure 1 is taken from Ham et al. (1964) and at the time of their study was partly conjectural (Denison, personal communication to Hanson, 2014). However, recent geophysical models incorporating gravity, aeromagnetic, seismic, and other data suggest that rhyolites or rift-fill strata that could include intercalated rhyolites may, at least in places, extend even farther north than indicated in Figure 1 (Keller and Stephenson, 2007; Buckey, this guidebook).

Ham et al. (1964) pointed out that exposures of rhyolite in the Arbuckles are restricted to areas south of the Washita Valley Fault Zone (Figs. 1 and 2), one of the main reverse faults active during Pennsylvanian inversion of the aulacogen. They also noted that 1.4 km of rhyolitic strata were penetrated by the Franklin 1 Sparks Ranch well south of the fault zone. Mesoproterozoic basement rocks of the Eastern Arbuckle Province are exposed north of the fault zone, and the Reagan Sandstone unconformably overlies both these older rocks and the thick succession of rhyolites to the south. The absence of extrusive rhyolites north of the fault zone led Ham et al. (1964) to infer that the latter feature originated as a Cambrian normal fault that delimited the northern extent of the rhyolites in the Arbuckle region. However, Denison (1995) described rhyolite dikes that intrude the Mesoproterozoic rocks north of the fault zone and typically trend northwest, parallel to the inferred rift margin. He suggested that at least some of these dikes are Cambrian, an interpretation that has been confirmed by the ~536 Ma U-Pb zircon date obtained by Thomas et al. (2012) for one of these dikes (discussed above). It seems likely that at least some of these dikes fed surface eruptions, suggesting that a certain amount of rhyolite was extruded north of the Washita Valley Fault Zone but was removed by erosion prior to and during Reagan deposition.

The inferred subsurface distribution of the rhyolites shown in Figure 1 covers an area of ~40,000 km^2. Given the uncertainties discussed above, this figure may not be far from the true value. The thickest exposed stratigraphic section of the Carlton Rhyolite occurs in the Bally Mountain area in the Slick Hills (Fig. 3), north of the main mass of igneous rocks exposed in the Wichita Mountains, and is described in more detail in Hanson et al. (this guidebook). At Bally Mountain, the rhyolite succession is ≥2 km thick. The top is defined by the unconformity at the base of the Reagan Sandstone, and the base is defined by the Blue Creek Canyon Fault which places the rhyolites over Arbuckle Group strata to the west. It is unclear to what extent the thickness exposed at Bally Mountain is representative of other parts of the Carlton Rhyolite Group. If we assume an average thickness of 1 km for the rhyolites, which is probably con-

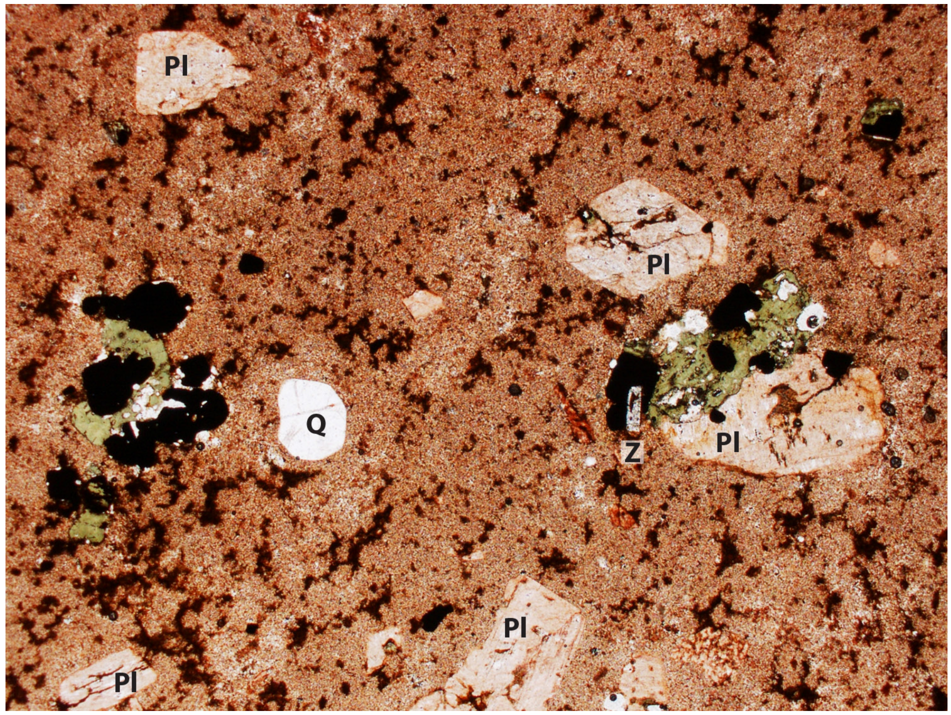

Figure 4. Photomicrograph showing phenocrysts and glomerophenocrysts in Carlton Rhyolite at Bally Mountain. Larger opaque grains are primary titanomagnetite. Several pseudomorphs of green clay replacing mafic silicate phenocrysts are visible. *Pl*: plagioclase; *Q*: quartz; *Z*: zircon intergrown with magnetite. Groundmass consists of finely intergrown quartz and feldspar with tridymite needles (inverted to quartz) barely visible at this scale. Irregular dark areas in groundmass are secondary hematite. Plane-polarized light; field of view ~5 mm across.

servative, the total volume of Cambrian rhyolite preserved in southern Oklahoma and adjacent parts of Texas could be on the order of 40,000 km^3. The related Wichita granites represent a significant additional amount of felsic magma emplaced at shallow crustal levels, but how much of the rhyolitic volcanic field is underlain by these granites is unknown, making it difficult to arrive at even an approximate estimate of their volume.

An important recent development has been the discovery that the rhyolites are intercalated with significant amounts of basalt and andesite in the subsurface in the Arbuckle Mountains area (Puckett et al., this volume). The base of the bimodal volcanic succession has not been reached in any of the wells drilled in the area, so that the total thickness of volcanic rocks in the aulacogen remains unknown. The presence of these subsurface basalts and andesites intercalated with the rhyolites raises a question concerning stratigraphic nomenclature. The name Carlton Rhyolite Group does not adequately describe this lithological package. If future subsurface work elsewhere in the aulacogen reveals equivalent amounts of mafic to intermediate lavas, perhaps the name Carlton Rhyolite Group should be replaced with Carlton Volcanic Group.

MINERALOGY AND ALTERATION

Primary Igneous Mineralogy

Phenocrysts in the Carlton Rhyolite are predominantly feldspars, titanomagnetite, and altered mafic silicates (Fig. 4). Quartz phenocrysts are less abundant overall and are absent in some flows. Glomerophenocrysts comprising aggregates of the various phenocryst types are common and in some cases consist of ten or more individual crystals. Accessory minerals include zircon and apatite.

Quartz phenocrysts show typical dipyramidal crystal forms with rounded or embayed margins (Figs. 4 and 5). Feldspar phenocrysts consist of alkali feldspar and plagioclase. The alkali feldspar is now orthoclase (where not altered) but was presumably either sanidine or anorthoclase prior to inversion and exsolution. Resorption textures are common in the alkali feldspar phenocrysts (Fig. 5), indicating disequilibrium with the magma prior to or during ascent from the magma chamber. Relict augite and aegirine or aegirine-augite are visible in some rhyolite thin sections from the West Timbered Hills in the Arbuckle Mountains (Eschberger and Hanson, paper, this guidebook). A few flows also contain minor amounts of primary biotite that shows various degrees of alteration but is well preserved in some cases. In general, however, the mafic silicate phenocrysts are completely replaced by secondary minerals described below. The pseudomorphs typically have relatively short, prismatic shapes (Fig. 4), suggesting they replaced pyroxene. Pseudomorphs that preserve conchoidal fractures are present in smaller amounts and are inferred to have replaced fayalite, based on their distinctive habits (Fig. 6).

The groundmass of the rhyolites consists largely of a quartzo-feldspathic intergrowth that in many cases shows

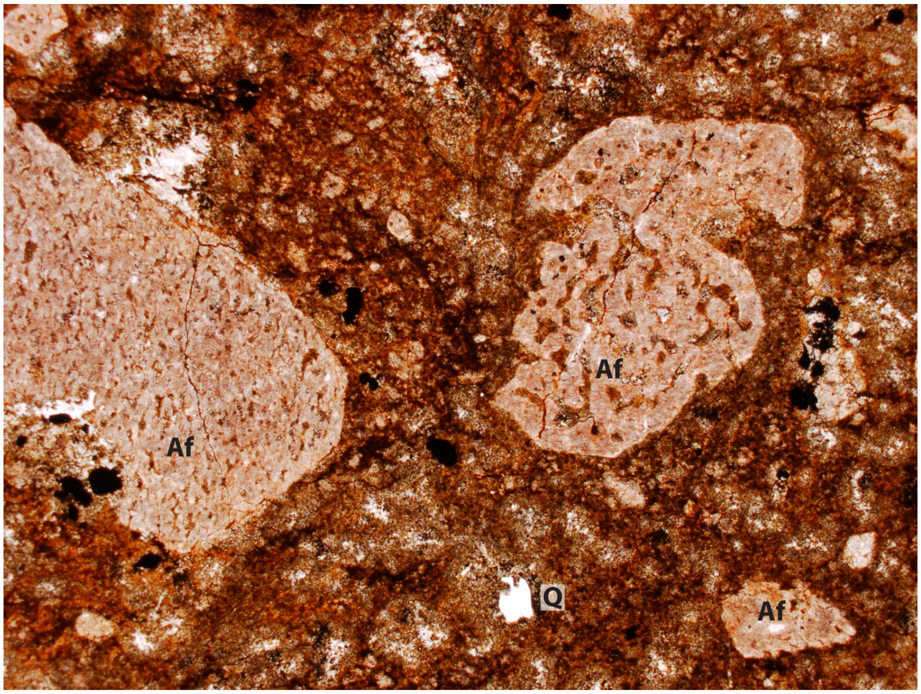

Figure 5. Photomicrograph showing alkali feldspar phenocrysts (*Af*) with resorption textures in rhyolite exposed northwest of Bally Mountain. Groundmass exhibits fine-scale spherulitic texture. *Q*: embayed quartz phenocryst. Plane-polarized light; field of view ~5 mm across.

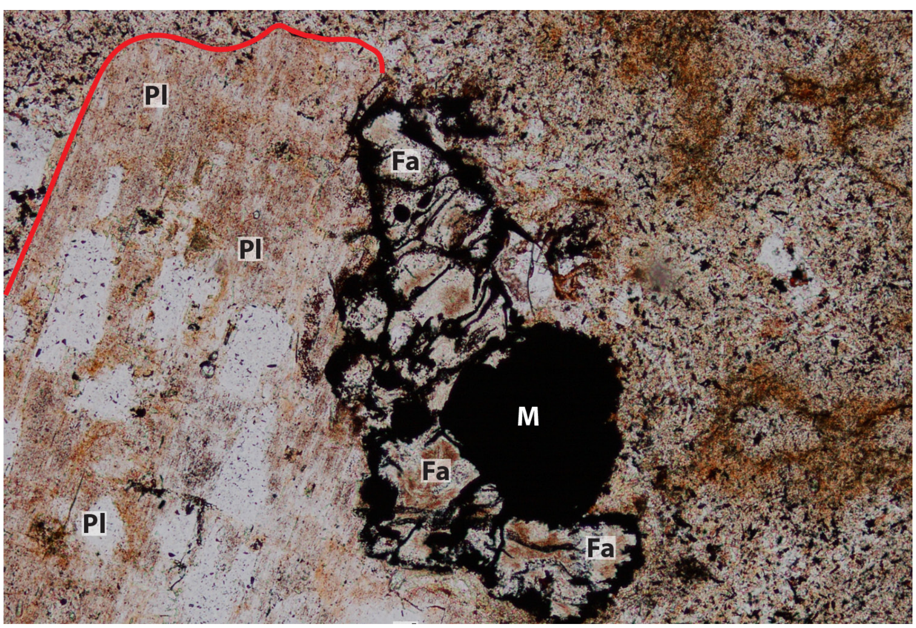

Figure 6. Photomicrograph of rhyolite at Bally Mountain showing glomerocryst consisting of plagioclase (*Pl*, outlined in red), titanomagnetite (*M*), and clay pseudomorphs interpreted to have replaced fayalite (*Fa*). Edges of original fayalite crystals and conchoidal fractures within crystals are outlined by very fine grained opaque magnetite and hematite. Plane-polarized light; field of view ~1.3 mm across.

a variety of textures related to flow emplacement and subsequent hydration and devitrification of glass. These textures are discussed in more detail in other papers on the rhyolites in this guidebook. A notable feature in the groundmass of the majority of the rhyolites that deserves special attention here is the presence of abundant thin, needle-like quartz crystals (Fig. 7) that are typically ≤0.4 mm in length. This is an unusual habit for quartz in the groundmass of rhyolites. Virtually identical textures, however, have been documented in some other examples of A-type felsic units described in the literature (Twist and French, 1983; Green and Fitz, 1993; Trendall, 1995), where the quartz needles are considered to be paramorphs after the higher-temperature silica polymorph tridymite. We follow this interpretation here.

Formation of tridymite under equilibrium conditions requires a temperature >870º C at a pressure of 1 bar (Deer et al., 2004). Such temperatures in themselves are not unusual for A-type rhyolites. In the Carlton Rhyolite, the tridymite crystals either are randomly oriented in the groundmass or form open, radiating clusters extending out from finer grained spherulites and therefore must have developed after the flows came to rest. If the tridymite crystallized as an equilibrium phase, the lavas must have ceased moving above 870º C. One problem with this interpretation, however, is that numerous examples of tridymite that crystallized outside of its equilibrium stability range are known in felsic volcanic rocks (e.g., Larsen et al., 1936; Eales, 1974; Deer et al., 2004), making it difficult to use the presence of groundmass tridymite in the Carlton Rhyolite as a robust constraint on the temperatures of the lavas.

Alteration

All of the rhyolites show alteration of the phenocrysts and groundmass to varying degrees. Secondary minerals include

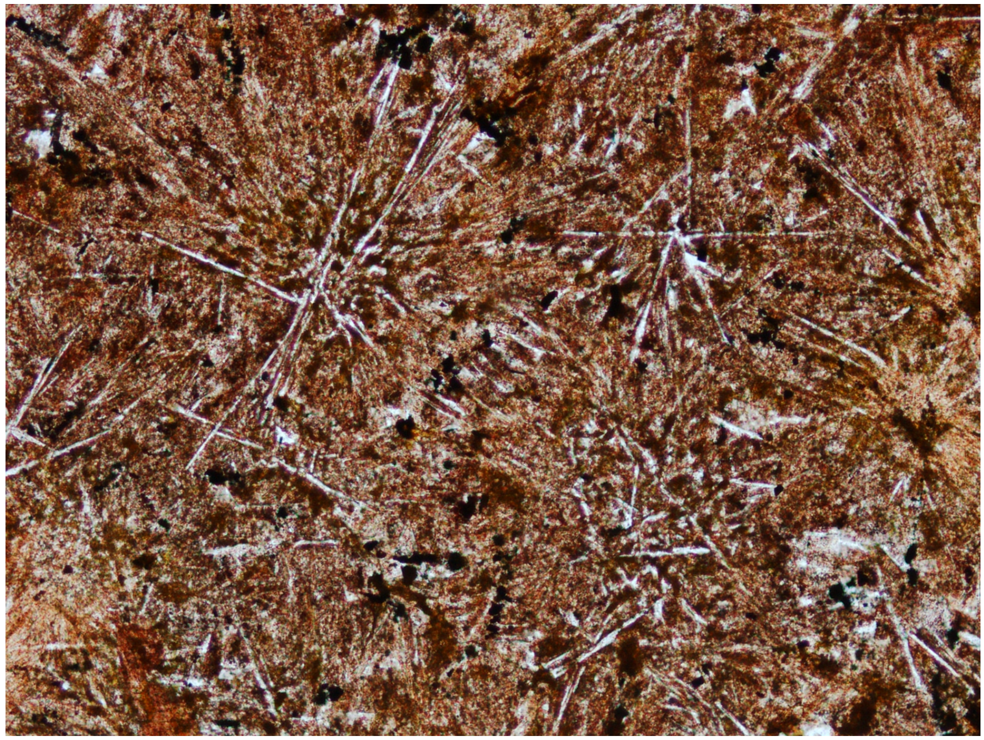

Figure 7. Photomicrograph of rhyolite at Zodletone Mountain showing radiating or randomly oriented needle-like tridymite crystals (inverted to quartz) in rhyolite groundmass. Plane-polarized light; field of view ~1.3 mm across.

sericite, carbonate, fluorite, hematite, leucoxene, and clay minerals. Hematite is abundant as disseminated "dust" within the groundmass, giving the rhyolites a typical reddish or orangish tint, and also occurs together with leucoxene as an alteration product of primary titanomagnetite. The clay minerals range from colorless to green (Figs. 4 and 6), and some of the green clay shows the typical low, anomalous interference colors of chlorite. In many cases, however, the birefringence is significantly higher, suggesting that the green clay is possibly an iron-rich smectite (Nesse, 2013), although this requires confirmation by X-ray diffraction. Here we use the general term "green clay" to refer to all the green clays of secondary origin in the rhyolites.

Pseudomorphs after the primary mafic silicates consist dominantly of green clay (Fig. 4) intergrown with secondary Fe-Ti oxides which include discrete grains of magnetite and extremely fine-grained particles of hematite and leucoxene. Where the hematite is abundant it imparts a reddish color to the pseudomorphs. The feldspars are altered to varying degrees to carbonate, sericite, and green clay. In some cases, chessboard albite has replaced the original alkali feldspar phenocrysts and is recognized by its distinctive twinning (fig. 10B, Puckett et al., this guidebook; fig. 20D, Eschberger et al., paper, this guidebook). Chessboard albite forms by Na metasomatism of alkali feldspar, and the twinning develops to relieve the internal strain caused by the shift from the original monoclinic alkali feldspar to triclinic albite (Smith, 1974).

The timing of the alteration is not always clear, but some of it probably occurred when volcanic gases and hydrothermal fluids circulated within the volcanic pile as it accumulated. Additional hydrothermal activity was likely driven by intrusion of granite into or beneath the volcanic succession (e.g., Ham et al., 1964; Finegan and Hanson, this guidebook). In some rhyolite outcrops in the Wichita Mountains (Philips, 2002) the feldspars show intense sericitization near faults that were active during Pennsylvanian inversion of the aulacogen, suggesting that the sericite formed from hydrothermal fluids migrating along these faults. In the western Arbuckle Mountains, paleomagnetic data similarly indicate that a significant amount of the alteration affecting the rhyolites occurred during late Paleozoic deformation (Elmore et al., 1998).

GEOCHEMISTRY

Major- and trace-element data for 102 samples of the Carlton Rhyolite collected from outcrops in the Wichita and Arbuckle Mountains and from basement wells in the Arbuckle Mountains region are presented in Figures 8 through 11 in order to give an idea of the compositional ranges and magmatic affinities shown by the rhyolites as a whole. The plotted samples include two from rhyolite xenoliths within granite and two from rhyolite dikes cutting granite in the Wichita Mountains and are taken from Price (1998). Also included are six samples from extrusive units in the western Arbuckle Mountains taken from Price et al. (1998b). The other data come from samples collected by Hanson, Bob Puckett, and TCU students and were analyzed at the GeoAnalytical Laboratory at Washington State University, following their standard XRF and ICP-MS techniques for major and trace elements (wsu.edu/facili-

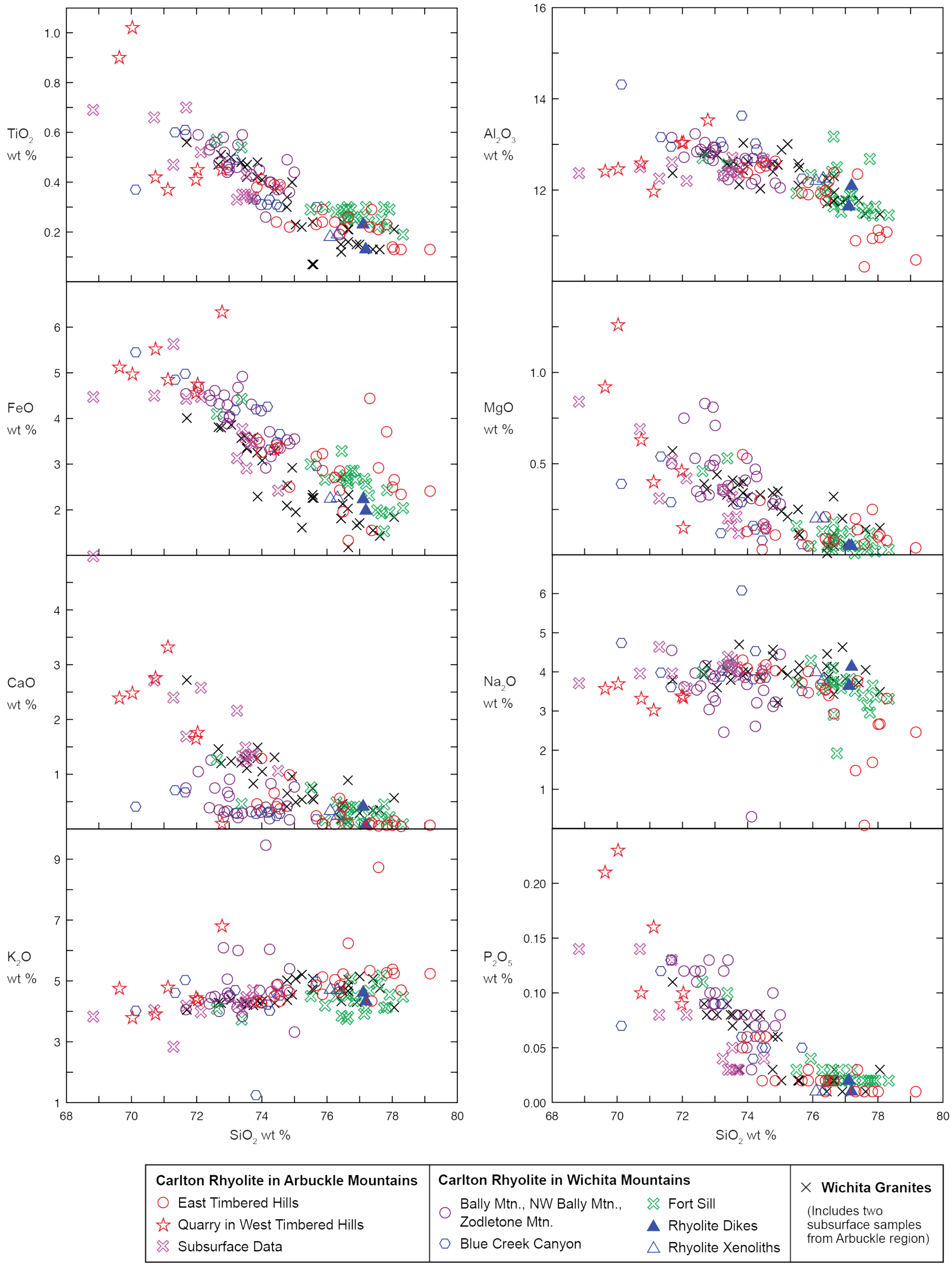

Figure 8. Harker diagrams for major oxides for the Carlton Rhyolite and Wichita granites.

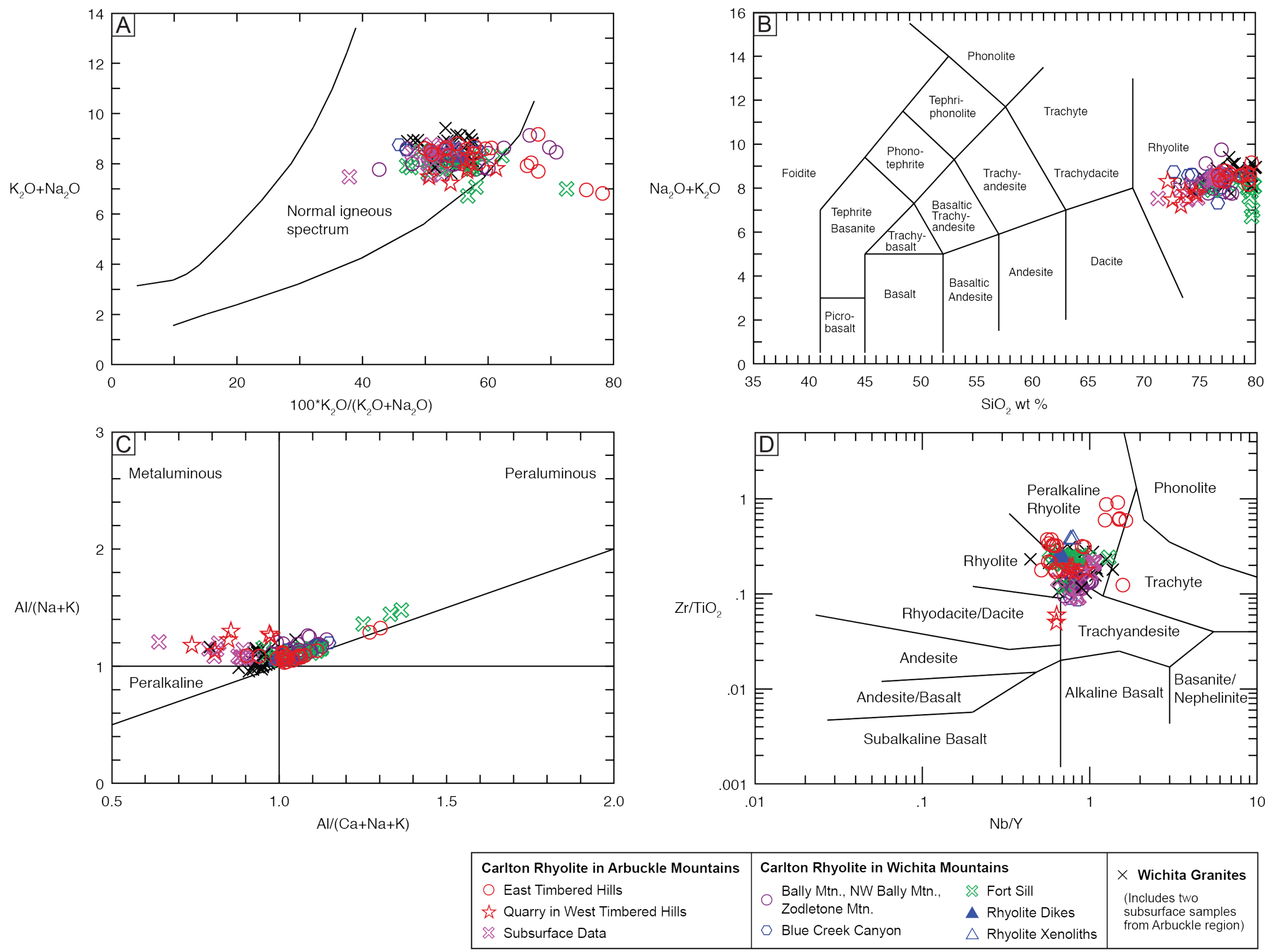

Figure 9. Data for the Carlton Rhyolite and Wichita granites plotted on selected diagrams. (A) Igneous spectrum diagram of Hughes (1972). (B) Total alkalis versus silica (TAS) diagram of Le Bas et al. (1986). (C) Alumina saturation diagram of Maniar and Piccoli (1989). (D) Discrimination diagram of Winchester and Floyd (1977).

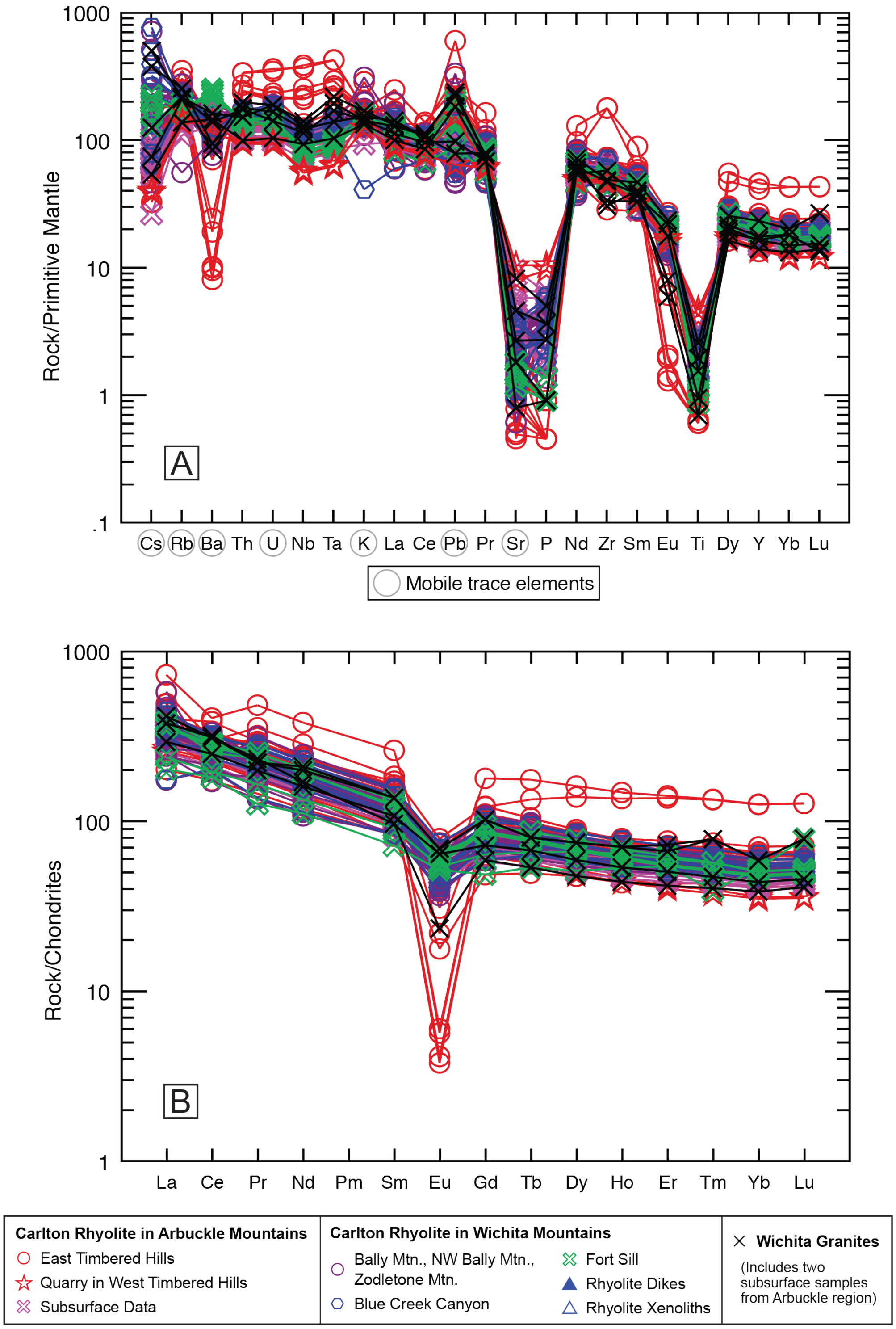

Figure 10. Multi-element diagram (A) and REE diagram (B) for the Carlton Rhyolite and Wichita granites. Normalization values in both diagrams are from Sun and McDonough (1989).

ties/geolab/). These analytical data are tabulated in other papers on the Carlton Rhyolite in this guidebook where the data are also discussed in more detail with regard to specific study areas. All of the data are reported volatile-free and have been normalized to 100%. Each of the samples analyzed at Washington State University has also been studied petrographically in order to evaluate the effects of secondary alteration on major- and trace-element contents. Representative data for the Wichita granites are shown in Figures 8 through 11 for purposes of comparison and are taken from Price (1998), except for two subsurface granite samples discussed in Puckett et al. (this guidebook).

Silica values in the rhyolites range from 68.83 to 79.16 wt % (Fig. 8). A few of the rhyolites with the highest silica values have experienced secondary silicification, and some of the spread in data for individual study areas is also the result of silica mobility (e.g., Eschberger et al., paper, this guidebook; Finegan and Hanson, this guidebook). However, there is no petrographic evidence for significant modification of original silica contents in the majority of the rhyolites, and most of the range in silica values shown in Figure 8 is believed to be primary. The granite data have fairly similar trends to the rhyolites but do not overlap with the less-evolved rhyolite compositions. This may reflect a real difference or may simply be the result of a greater number of analyses for the rhyolites.

Overall, TiO_2, FeO, MgO, CaO, and P_2O_5 decrease with increase in silica (Fig. 8), consistent with fractionation of observed phenocrysts and accessory minerals. There is, however, considerable scatter in the data in some of the plots. This may partly indicate that rhyolite samples with distinct petrogenetic histories or fractionation trends have been lumped together, but can also be attributed to element mobility during alteration. Several samples are either unusually high or low in K_2O or Na_2O, indicating significant disturbance of the alkalis, which is also illustrated by the fact that a number of the samples fall outside the normal igneous spectrum in the Hughes (1972) diagram shown in Figure 9A.

All of the data fall in the rhyolite field in the TAS diagram of Le Bas et al. (1986) (Fig. 9B), but this diagram should obviously be used with caution in altered rocks where both the alkalis and silica may have been disturbed. None of the rhyolite samples plot in the peralkaline field in Figure 9C, although some of the granites do. This is consistent with the presence of aegirine and arfvedsonite or riebeckite in some of the granites, which in general show better preservation of primary mafic minerals than in the rhyolites (Myers et al., 1981; Gilbert et al., 1990). Peralkaline rocks, by definition, are those in which $Na_2O + K_2O$ is greater than Al_2O_3 in molecular proportions. Loss of alkalis during alteration, however, can readily destroy an original peralkaline signature (e.g., Tollo et al., 2004), even when diagnostic peralkaline minerals are still preserved (McKay and Rogers, 1970). Figure 9C is therefore likely to be of questionable value in the case of the Carlton Rhyolite, which may have been more susceptible to secondary modification of major-element contents than the granites. In altered volcanic rocks of this type, Figure 9D from Winchester and Floyd (1977) is likely to be more useful because it employs ratios of elements known to be resistant to secondary disturbance. Many of the rhyolite samples plot well into the peralkaline field in Figure 9D. Assuming this diagram provides a reliable indication of peralkaline compositions, it appears that much of the Carlton Rhyolite Group was originally peralkaline.

Samples for which complete trace-element data are available are plotted in a multi-elelment diagram normalized to primitive mantle in Figure 10A. Some of the more mobile elements (circled on the *x* axis in the figure) show considerable variation, partly reflecting secondary alteration. Most of the samples, however, have closely similar patterns, including depletions in Sr, P, Eu, and Ti that record fractionation of feldspar, apatite, and titanomagnetite. Many of the rhyolites have slight negative Nb and Ta anomalies, although these are absent in some samples from the East Timbered Hills in the Arbuckles, which also show more strongly fractionated patterns than the other samples. The REE patterns in Figure 10B are also very similar in the rhyolites as a whole except for the more highly fractionated samples from the East Timbered Hills. Data for the Wichita granites tend to plot with the majority of the rhyolite samples in both diagrams.

The rhyolite and granite samples fall together in fields for within-plate, A-type felsic rocks in the discrimination plots in Figures 11A and 11B which rely on elements known to be resistant to alteration. Most of the data cluster tightly in those two diagrams, in keeping with the results from Figure 10. Three useful discrimination diagrams developed by Eby (1990, 1992) for A-type felsic rocks are shown in Figures 11C, 11D, and 11E. In the triangular diagrams in Figures 11C and 11D the data straddle the boundary between the A1 and A2 fields, indicating derivation of the felsic magmas partly from ocean-island-basalt-type sources, but with contributions from sources previously modified by subduction-zone processes. This point is also made in Figure 11E, where some of the rhyolite samples fall well into the field for rocks derived from ocean-island-basalt (OIB) sources, but the majority of the data define a clear

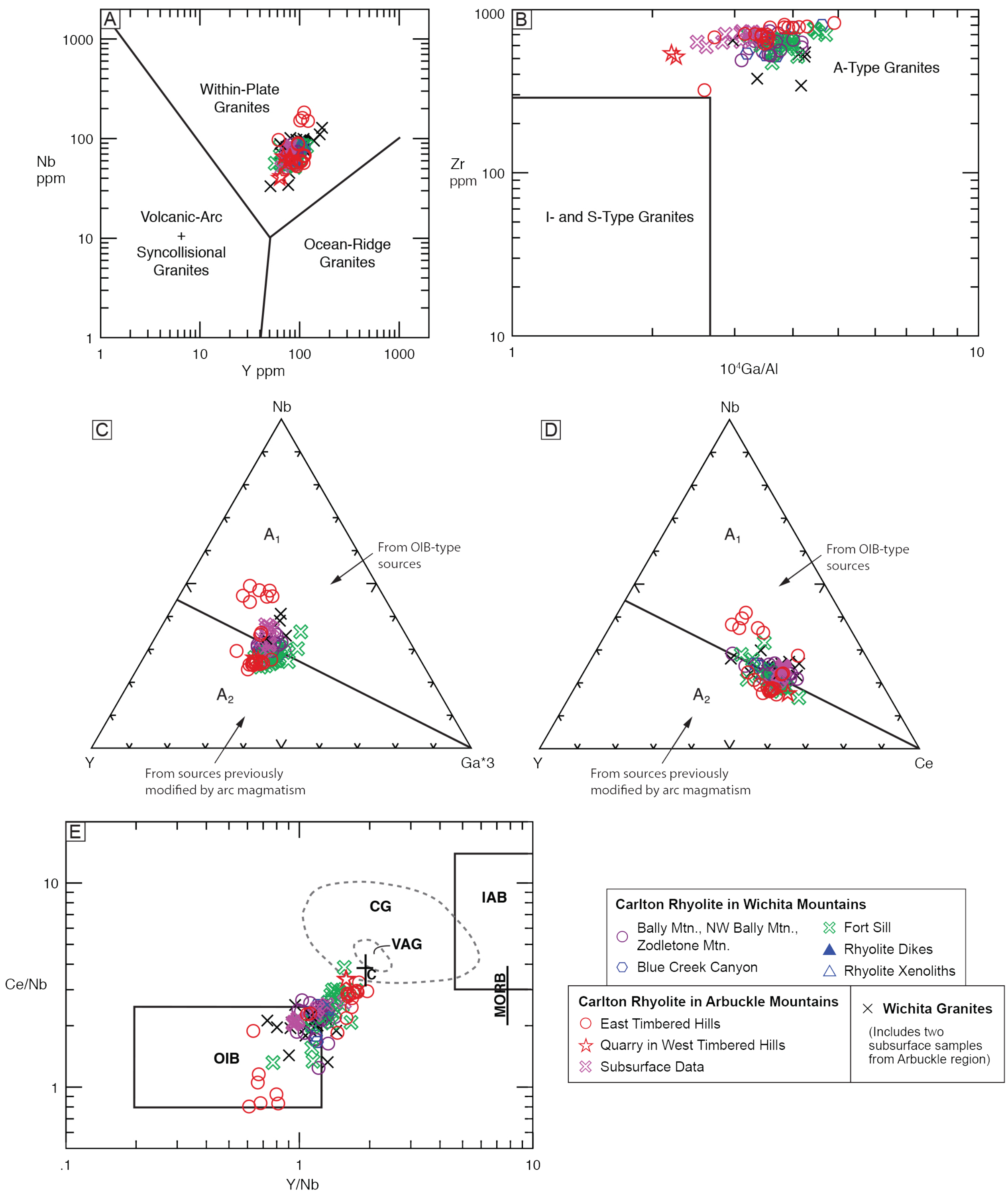

Figure 11. Data for the Carlton Rhyolite and Wichita granites plotted on trace-element discrimination diagrams. (A) Nb versus Y discrimination diagram of Pearce et al. (1984). (B) Zr versus 10^4Ga/Al discrimination diagram of Whalen et al. (1987). (C) Y-Nb-Ga discrimination diagram of Eby (1992) for A-type felsic rocks. (D) Y-Nb-Ce discrimination diagram of Eby (1992) for A-type felsic rocks. (E) Ce/Nb versus Y/Nb diagram of Eby (1990) for A-type felsic rocks. *MORB*: range for mid-ocean ridge basalts; *IAB*: field for island-arc basalts; cross labeled *C*: average crustal ratios; *CG*: field for syncollisional granite; *VAG*: field for volcanic-arc granite; *OIB*: field for ocean-island basalts.

trend extending from the OIB field to values for average continental crust and collisional granites derived by crustal anatexis. These results are consistent with the presence of negative Nb-Ta anomalies in many of the rhyolites and suggest that their petrogenesis involved some input from older crust.

Available isotopic data indicate that the Wichita granites and Carlton Rhyolite typically have low $^{87}Sr/^{86}Sr$ ratios and positive ε_{Nd} values that overlap with those for diabase intrusions in the Wichita Igneous Province (Hogan et al., 1995; Degeller et al., 1996; Wright et al., 1996). These data indicate that fractionation from more mafic precursors or partial melting of mafic rocks emplaced at deeper levels was the ultimate source of the felsic magmas. However, the trace-element data, which are available for a much larger suite of the felsic rocks than have been analyzed isotopically, suggest that crustal assimilation played a role in modifying the compositions of many of the magmas.

PHYSICAL VOLCANOLOGY

Work on the physical volcanology of the Carlton Rhyolite Group is hampered by the fact that so much of the unit is confined to the subsurface. Sufficient outcrops occur in the Wichita and Arbuckle Mountains, however, to gain some insight into lithofacies architecture and eruptive styles within the rhyolitic volcanic field. Studies of the exposed rhyolites, in turn, provide a template for interpretation of data from drill holes penetrating the volcanic succession (Puckett et al., this guidebook). To date, workers at TCU have mapped most of the exposed rhyolite outcrops in the Wichita Mountains (Finegan and Hanson, this guidebook; Hanson et al., this guidebook). Exceptions include small areas in the Slick Hills where we have not yet gained access to private property, and more extensive outcrops in the Fort Sill Military Reservation that are off limits because they occur within the artillery impact zone. Eschberger (2012) produced a detailed map of the rhyolites in the East Timbered Hills in the Arbuckles (see also Eschberger et al., paper, this guidebook), and we are now beginning studies of the more extensive rhyolite outcrops in the West Timbered Hills in collaboration with the Oklahoma Geological Survey.

We have identified 31 different rhyolite flows in the Wichita Mountains and two more in the East Timbered Hills in the Arbuckles. The flows occur in stacked vertical sequences. Where exposures are good, many of the flows are separated by thin (≤1 m) interbeds of tuffaceous mudstone and/or rhyolitic ash-fall tuff containing bubble-wall shards (Fig. 12). Less commonly, one flow rests directly on the underlying one without any obvious evidence for a break in time. Examples are also known both in the Wichitas and in the East Timbered Hills where flows are separated by sequences as much as 100 m thick of tuffaceous rocks intercalated with coarser volcaniclastic deposits containing reworked rhyolitic debris. Sedimentary structures in these sequences indicate deposition in lakes that must have existed for some length of time.

The available outcrops provide good cross-sectional views of the flows. So far we have not found exposures of lateral flow terminations, but outcrops of one flow in the Slick Hills in the Wichita Mountains may be close to the original edge of that flow (Hanson et al., this guidebook). Flow breccia occurs at the bases and/or tops of some flows but is absent in others. Many of the flows have a distinctive internal structure in which flow banding is restricted to discrete, relatively narrow zones near the bases and tops of the flows, which also show evidence of having been originally glassy following emplacement. In contrast, flow interiors consist of massive, homogeneous felsitic rhyolite with a monotonous appearance in the field. These felsitic interiors show extensive development of randomly oriented tridymite needles in the groundmass, as described above, and the needles typically increase in size toward the centers of flows, indicating that the flow interiors underwent slow, uniform cooling after the lava came to rest. Flows for which both the bases and tops are exposed generally are ~80 to ~230 m thick, much of which typically is homogeneous felsite. Thicker examples also occur, however, and include a 400-m-thick flow on Bally Mountain in the Slick Hills (Hanson et al., this guidebook) and a 600-m-thick flow in the East Timbered Hills (Eschberger et al., paper, this guidebook), which is the thickest flow so far documented in the Carlton Rhyolite Group.

It is difficult to understand how this type of internal zonation could develop if these units were emplaced as domes or short, thick lava flows of the type commonly formed by highly viscous rhyolite lava. We instead interpret the rhyolite outcrops showing this distinctive zonation to represent erosional remnants of laterally extensive flows similar to those documented in a number of other A-type felsic volcanic provinces. Some of these units have been referred to as "flood rhyolites" (e.g., Henry and Wolff, 1992), and examples of single felsic lavas forming broad, tabular sheets that can be traced laterally for tens of kilometers have been described in the literature (e.g., Henry et al., 1988, 1990; Henry and Wolff, 1992; Allen et al., 2008; Branney et al., 2008). One well-documented example has

Figure 12. Photomicrograph showing silicified bubble-wall shards in tuff interbed between rhyolite flows exposed northwest of Bally Mountain. Plane-polarized light; field of view ~5 mm across.

a preserved length of 225 km (Allen and McPhie, 2002). The ability of A-type felsic lavas to flow for considerable distances is interpreted to reflect relatively low magmatic viscosities resulting from a combination of factors including high magmatic temperatures and high contents of fluorine dissolved in the magma (e.g., Henry and Wolff, 1992; Green and Fitz, 1993; Dingwell et al., 1985; Agangi et al., 2012). High effusion rates and the development of chilled margins that effectively insulate flow interiors are additional factors leading to formation of these extensive felsic lavas (Manley, 1992).

We can trace most individual Carlton Rhyolite flows no farther than a few kilometers laterally because of the limited nature of the outcrops. One exception occurs in the Fort Sill area in the Wichita Mountains where a single rhyolite flow extends for ~18.5 km before becoming covered or being truncated by intrusive granite (Finegan and Hanson, this guidebook). The original extent of this flow could have been much larger.

Extensive extrusive units in A-type felsic provinces that may resemble lava flows can also form from pyroclastic flows that are generated by explosive eruptions and undergo partial or complete homogenization during or after transport to form lava-like rheoignimbrites (e.g., Branney and Kokelaar, 1992; Andrews and Branney, 2011). In rheoignimbrites, evidence for a pyroclastic origin (e.g., eutaxitic texture) may be preserved in the rapidly chilled basal parts of the flows (Henry and Wolff, 1992). Most flow units in the Carlton Rhyolite lack pyroclastic textures, even at their bases. Textures resembling eutaxitic texture defined by welded pumice fragments do occur at the bases of a few flows in the Slick Hills (Hanson et al., this guidebook), but such textures can also develop from welding of pumice formed by vesiculation during emplacement of effusive lava (Manley, 1995). Our preferred interpretation is that most or all of the flows we have examined in the Carlton Rhyolite Group are effusive lava flows. We cannot eliminate the possibility that some of the flows originated as rheomorphic ignimbrites, but if so they must have been nearly completely homogenized so as to travel in a lava-like state for some distance before coming to rest.

No source vents for the Carlton Rhyolite have been reported in previous studies, although some workers have speculated that the rhyolites were fed from fissure-type eruptions (e.g., McConnell and Gilbert, 1990; Hogan et al., 1998). In support of this idea, we have recently documented a feeder dike to one of the flows exposed on Bally Mountain in the Slick Hills (Hanson et al., this guidebook). The lack of pyroclastic textures in either the dike or flow is convincing evidence that this particular flow erupted directly from the vent as lava (cf. Henry and Wolff, 1992).

Ongoing studies of the Carlton Rhyolite Group in the subsurface in and near the Arbuckle Mountains provide additional evidence for the presence of vertically stacked rhyolite flows lacking pyroclastic textures (Puckett et al., this guidebook). The general paleogeographic scenario suggested by the surface and subsurface studies involves repeated eruption of felsic lavas (and possibly thoroughly homogenized rheoignimbrites) in various parts of the evolving Cambrian rift. Lakes formed at times between eruptions, possibly when drainage systems were blocked by emplacement of large flows. Tuff interbeds with bubble-wall shards typically occur only in minor amounts between flows, suggesting that large-scale pyroclastic eruptions involving formation of major eruption columns played little role in the volcanic evolution of the rift, or at least in those parts of the rhyolitic volcanic field that we have so far been able to study.

Of course, we still have seen only a small part of the mostly buried Carlton Rhyolite Group, and there may be considerable lithofacies variations remaining to be discovered in other parts of the volcanic field. An example is provided by the Franklin 1 Sparks Ranch well discussed above. Of the total thickness of 1.4 km of strata penetrated by that well and assigned to the Carlton Rhyolite Group, ~1 km consists of texturally immature volcaniclastic deposits containing silt- to gravel-size rhyolitic detritus and intercalated with much less abundant rhyolite lavas (see fig. 2, Puckett et al., this guidebook). Results from this well indicate that significant accumulations of reworked rhyolitic sedimentary rocks may remain to be discovered in other parts of the buried volcanic succession within the Southern Oklahoma Aulacogen, perhaps forming thick volcaniclastic aprons that interfinger laterally with lavas around major eruptive centers.

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