Stop 1. Mill Creek Quarry diabase dikes, eastern Arbuckle Mountains, Oklahoma

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Location: Entrance to quarry is on the west side of OK Hwy 12 ~4.5 mi south of Mill Creek and ~1.7 mi north of Troy, Johnston County, Oklahoma. The quarry occupies much of the W½ of sec. 29, T. 2 S., R. 5 E. and areas immediately to the north and west, Troy 7.5' quadrangle. Approximate UTM coordinates: 701400E, 3804040N. The quarry is owned and operated by Martin-Marietta Materials and permission is required to enter.

INTRODUCTION

The Mill Creek Quarry (also known as the Martin Marietta Quarry and previously as the Meridian Quarry) is located in the northern part of the USGS Troy 7.5–minute quadrangle, Johnston County, Oklahoma (Figure 1A). The host rock in the quarry is the Troy Granite, which is cut by numerous diabase dikes. The quarry produces crushed stone that is used mainly as railroad ballast. The ballast is widely used and can be easily identified by the mixture of dark diabase and pink granite clasts. The diabase has a very high crushing strength making it difficult to crush the material with standard equipment.

The most striking feature of the quarry is the number and complexity of the diabase dikes. This quarry is the best exposure of diabase dikes in Oklahoma and probably the central interior of the United States. Denison (1973) mapped the area before the present quarry was opened and identified several diabase dikes in the poorly exposed area that included several three-dimensional stone quarries. On the basis of the field exposures there was no way to predict the number and volume of dikes within the Troy Granite. It was a surprise to the quarry operators as well.

The diabase dikes in the Mill Creek Quarry are part of a swarm of diabase dikes that are widespread throughout the core of the eastern Arbuckle Mountains. This swarm of dikes intrudes the 1400 to 1365 Ma granitoids of the eastern Arbuckles. The dikes strike predominantly N60°W (Figure 1B) parallel to the rifted margin of the Southern Oklahoma Aulacogen (SOA) (Denison, 1995). Most of the diabases are related to Cambrian opening of that structure and are referred to here as the Mill Creek diabase dike swarm for excellent exposures in the quarry. In addition, an unknown but probably small number of low–Th diabase dikes were emplaced near the age of the host granitoids. These, along with a suite of highly silicic northwest-trending microgranite porphyry dikes, record a Mesoproterozoic structural grain that may have influenced Paleozoic structure. Dikes from the two diabase suites cannot be easily distinguished petrographically but have distinct geochemical signatures, as discussed below.

The timing and tectonic setting of the younger diabases suggest that they were intruded in association with the break-up of the southern Laurentian supercontinent in the Early Cambrian. These dikes testify to the probable existence of the break-up of a large igneous province (LIP) in this region (Lidiak et al., 2005; Hanson et al., 2011, 2013) and demonstrate that Cambrian LIPs were compositionally similar to better-known break-up LIPs of Mesozoic and younger age. This occurrence is the only evidence that we can find for the presence of a LIP break-up in southern Laurentia, but we argue that compositional similarities with other, better-preserved LIPs warrant the conclusion that the Cambrian LIP break-up of the southern mid-continent was similarly extensive.

REGIONAL SETTING

The diabase dike swarm that intrudes Mesoproterozoic granitoids in the Arbuckle Mountains of southeastern Oklahoma occurs along the present northern margin of the SOA (Figure 2). The SOA is a prominent Paleozoic struc-

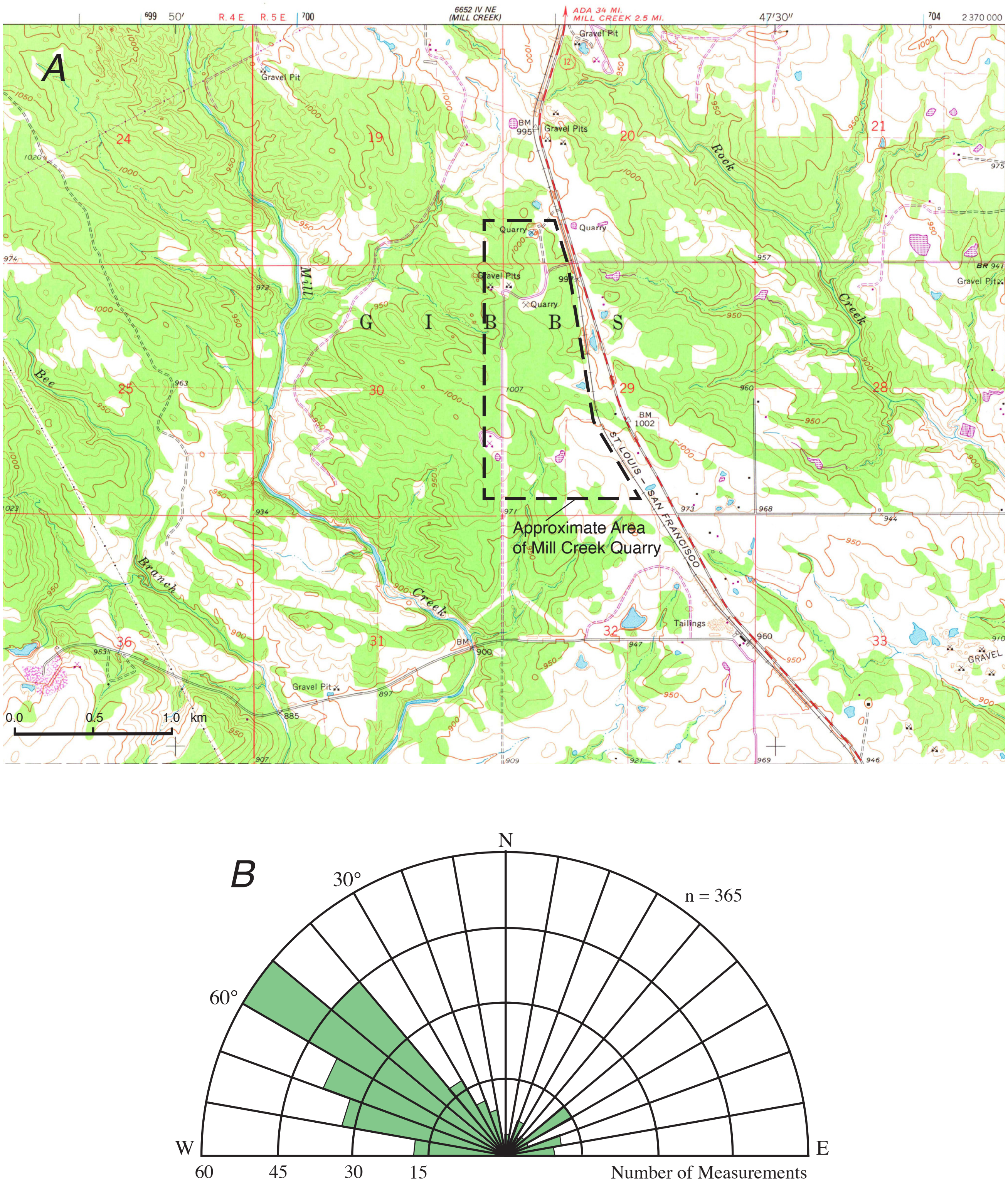

Figure 1. A) Location map of Mill Creek Quarry, Johnston County, Oklahoma. Base Map: USGS Troy 7.5-Minute Quadrangle (Topographic), 1963. For detailed coordinate location see Lidiak et al. (this guidebook, figure 3A). B) Rose diagram showing strike direction of diabase dikes, eastern Arbuckle Mountains, Oklahoma (Denison, 1995).

ture that is transverse to the Ouachita orogenic belt along the southern margin of the Laurentian (North American) craton. Similar Cambrian diabase dikes crop out about 200 km to the west in the Wichita Mountains (Gilbert, 1982, 1983; Price et al., 1996) and are present in the subsurface within the confines of the SOA (Ham et al., 1964; Puckett, 2011; Puckett et al., 2011).

AGES OF INTRUSION

Field and K-Ar isotope data suggest that a major period of diabase-dike emplacement occurred during Cambrian extension at about 540 to 530 Ma. Available K-Ar whole-rock dates for eastern Arbuckle diabase dikes are listed elsewhere (see Lidiak et al., this guidebook, table 1). Three of the ten dates are in the expected ~500 Ma age range, and two others are ~1300 Ma. The other five samples give dates of 748, 795, 1098, 1532, and 2074 Ma; these dates do not correspond to ages of rocks in the Arbuckles and may be too old due to inherited ^{40}Ar or too young due to ^{40}Ar loss. A concerted effort to extract and date zircons and/or baddeleyite from these dikes, as well as efforts to obtain reliable ^{40}Ar/^{39}Ar ages, is critically needed in order (1) to determine exactly when the inferred Cambrian (Mill Creek) dikes were emplaced in the SOA and (2) to test the idea that some of these Arbuckle diabase dikes are significantly older than Cambrian.

A Cambrian age of the Mill Creek diabases is suggested by the fact that diabase dikes in both the Arbuckle and Wichita areas cut the voluminous felsic volcanics of the Cambrian Carlton Rhyolite Group (Ham et al., 1964; Gilbert and Hughes, 1986; Hogan et al., 1998). These dikes represent the culmination of Cambrian igneous activity in the SOA. In addition, at least another episode of diabase dike intrusion in the eastern Arbuckles is indicated by cross-cutting diabase dikes in the Mill Creek Quarry and by the presence of two distinct geochemical suites within the diabases (discussed below). Indirect evidence for a significantly older (Precambrian?) age of one of the suites is suggested by a K–Ar date of 1291±26 Ma (Denison, unpublished Mobil data) on biotite from the Tishomingo Granite that is immediately adjacent to a five-meter-thick diabase dike in the Harris Quarry (Taylor, 1915). If this dike were Cambrian the K–Ar date should be partially reset.

PETROGRAPHY

The diabases are composed mainly of plagioclase, augite, and Fe-Ti oxides with or without olivine. Sphene, hornblende, biotite, quartz, and potash feldspar are found locally as trace minerals. Apatite is a ubiquitous accessory mineral. Chlorite, calcite, epidote, sericite, clays, and zeolites are very common and locally abundant as alteration minerals. The average grain size varies from 5 mm to 0.05 mm depending on the dike thickness and proximity to the margin. The texture varies from ophitic to subophitic to intersertal. Microamygdules are common in some dikes. Plagioclase phenocrysts are rare.

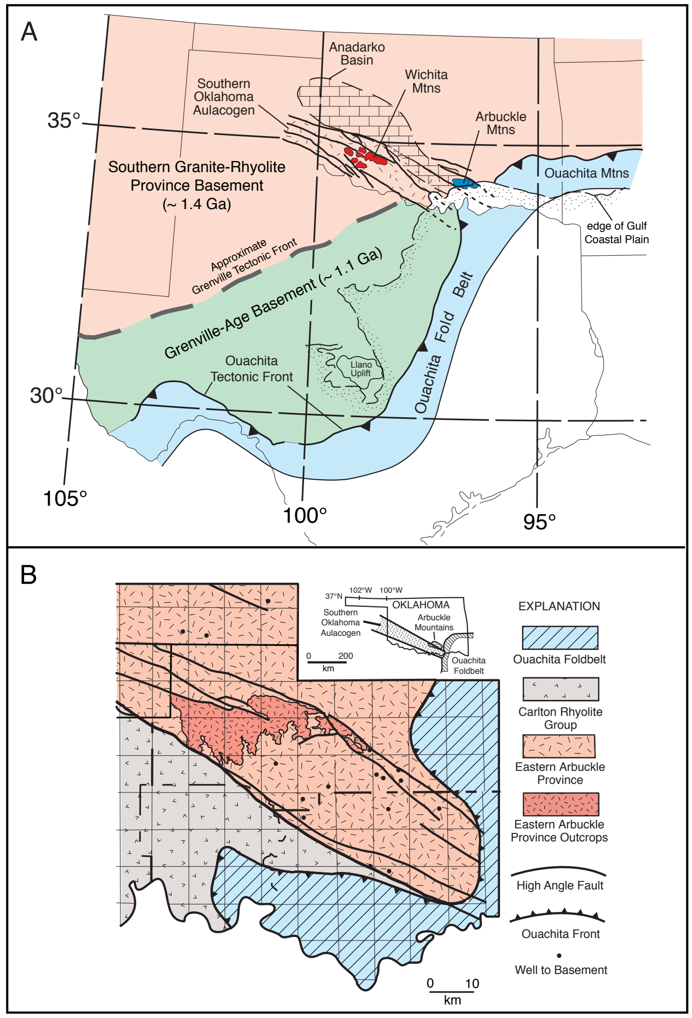

Figure 2. A) Generalized tectonic map of Texas and adjacent regions of Oklahoma and New Mexico. Base map and Phanerozoic structures adapted from Viele and Thomas (1989) with additions from Ham et al. (1964). Precambrian boundaries and provinces adapted from Ewing (1990, 1991) and Van Schmus et al. (1993). B) Main tectonic elements of southeastern Oklahoma adapted from Ham et al. (1964).

The Troy Granite in the Mill Creek Quarry forms two distinct phases. The typical Troy is a medium-grained pink granite that contains about one-third each of microcline perthite, plagioclase (~An_{20}), and quartz with minor biotite and trace amounts of sphene, opaque minerals, apatite, and zircon. Secondary minerals include minor sericite, chlorite, and epidote. A darker phase of the Troy in the quarry is characterized by an increase in plagioclase and biotite and a decrease in quartz and microcline perthite. Hornblende is present in small amounts in some samples. The contact relations between the typical and dark Troy phases are sharp and without chilling effects. The two phases are interpreted as being separate intrusions.

GEOCHEMISTRY

Major Elements

All of the analyzed Mill Creek diabase dikes are compositionally similar with restricted ranges in major-element compositions. The rocks are characterized by SiO_2 contents between 46 and 52 wt %, moderate to high TiO_2 (1.8 to 2.9 wt %), high Fe_2O_3 (12.6 to 15.5 wt %), low Al_2O_3 (13.3 to 15.7 wt %), and moderately low MgO (4.3 to 7.0 wt %). CIPW normative compositions are either olivine tholeiites or quartz tholeiites. They also display cation-normative (Irvine and Baragar, 1971) subalkaline compositions.

The diabases have experienced moderate amounts of crystal fractionation from more primitive mantle melts. This is shown by whole-rock MgO compositions, Mg# (=100*Mg/Mg + Fe) from 52 to 36, <70 to 120 ppm Cr, and 20 to 90 ppm Ni. Furthermore, major- and compatible-trace element variations (not shown here) define reasonably coherent trends with MgO or Mg# that are consistent with fractional crystallization playing an important role in the compositional variation.

The diabases are further characterized by high FeO^T/MgO ratios (FeO^T as total Fe). All of the Mill Creek diabases are high-Fe tholeiites according to the classification of Arculus (2003) (Figure 3). On the FeO^T/MgO plot, they are similar to other SOA diabases in the Wichita Mountains and in the nearby subsurface (Figure 3), suggesting that all of these rocks are part of a LIP within the SOA.

Trace Elements

Trace-element data are consistent with the major-element data in demonstrating tholeiitic affinities for the Arbuckle diabases. The tholeiitic character is indicated by low TiO_2 and P_2O_5 contents and low Nb/Y ratio. Furthermore, the diabases display a characteristic within-plate smooth incompatible-element pattern (Figure 4) with essentially no depletion in the high-field-strength element Nb (and Ta). Figure 4 also shows clearly that the Cambrian diabases are clearly distinct from their older low–Th counterparts in containing greater abundances of Th, Nb, Zr, Hf, and the LREE.

The Cambrian diabases are relatively enriched in incompatible elements compared to primitive mantle (Figure 4) with the more incompatible elements Nb, Ta, and the LREE being enriched by a factor of about 10 to 50. Of particular additional note is the relative depletion in Th for both the Cambrian and the older low-Th Arbuckle diabases. The depletion may reflect the presence of an anomalous dense mantle (Keller et al., 1983) beneath the SOA and the absence of any continental crustal material in the source region.

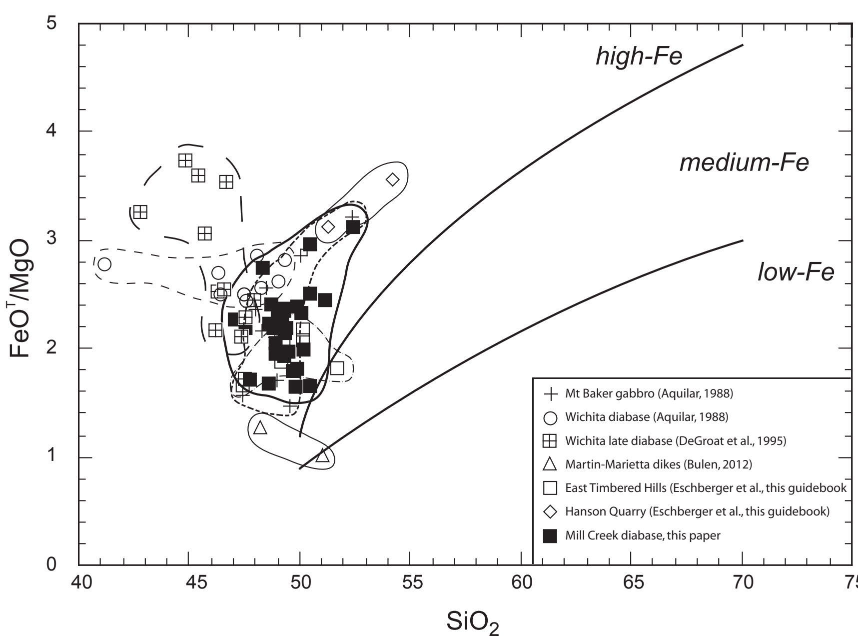

Figure 3. SiO_2 vs FeO^T/MgO diagram (Arculus, 2003) of Southern Oklahoma Aulacogen diabasic dikes. Sources: Mt. Baker gabbro and Wichita diabase (Aquilar, 1988); Wichita late diabase (DeGroat et al., 1995); Martin Marietta dikes (Bulen, 2012); East Timbered Hills (Eschberger et al., this guidebook); Hanson Quarry diabase (Eschberger et al., this guidebook); Mill Creek diabases (this paper).

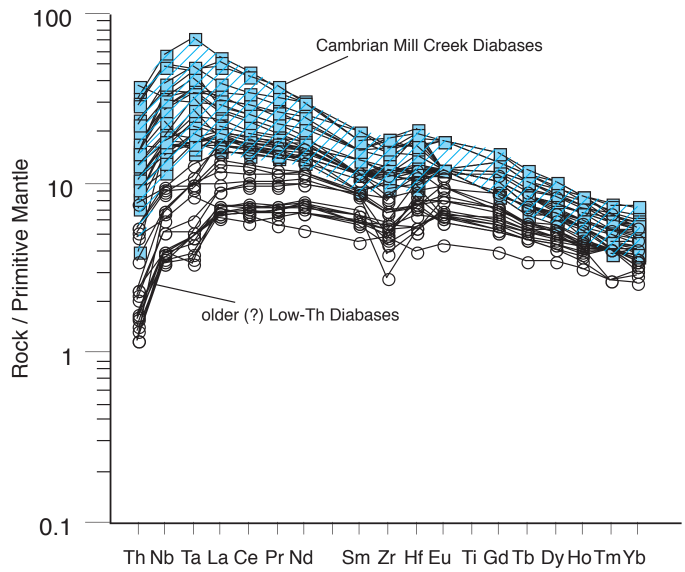

Figure 4. Normalized incompatible-element patterns of Arbuckle Cambrian Mill Creek diabases and older (?) low-Th Arbuckle diabase dikes normalized to primitive mantle. Normalizing factors from Sun and McDonough (1989).

Isotopic Ratios

Initial Sr and Nd isotopic compositions of seven Mill Creek quarry diabase dikes are plotted in Figure 5. They plot mainly in quadrant one on a typical $^{87}Sr/^{86}Sr$ vs ε_{Nd} diagram. Initial $^{87}Sr/^{86}Sr$ varies between 0.70387 and 0.70484. Initial ε_{Nd} is modestly positive, +1.6 to 5.1, indicating a significant contribution from depleted mantle. These ratios are closely similar to other SOA Cambrian mafic rocks (Lambert et al., 1988; Hogan et al., 1995, 1996) (Figure 5) and further support the idea that these rocks are part of an earliest Cambrian LIP and apparently part of the hypabyssal feeder system.

These isotopic compositions fall within the field defined by dominant oceanic mantle reservoirs N-MORB, HIMU, EM1 and EM2 and are also broadly similar to sub-continental lithospheric mantle (Figure 5). None of these rocks show any clear evidence for contamination by continental crust.

SUMMARY

The geochemistry (major, trace, and isotopic ratios) of Arbuckle Cambrian diabases are remarkably similar to basalts of Large Igneous Provinces (LIP).

The age and tectonic setting of Arbuckle Cambrian diabases are consistent with rifting and continental break-up during the Early Cambrian.

The Arbuckle Cambrian diabases are the remnants of an LIP that formed in what is now the southern Oklahoma aulacogen (SOA).

The Arbuckle Cambrian diabases show no evidence of any contamination by continental crust.

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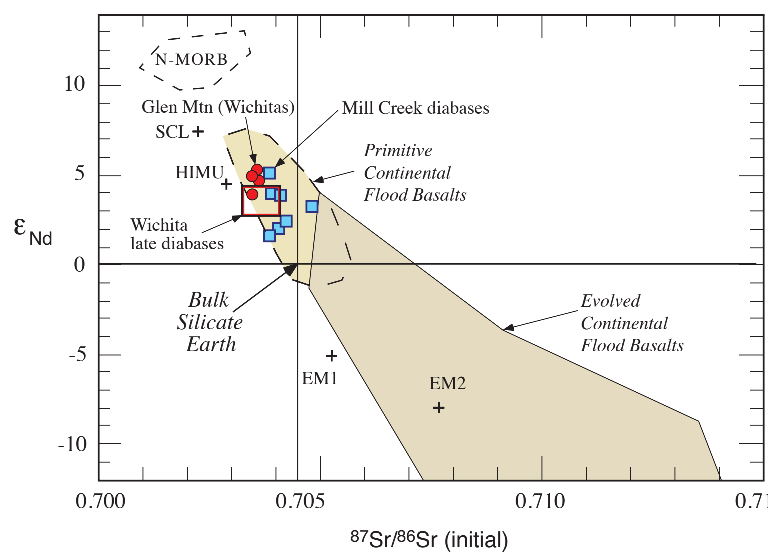

Figure 5. Sr and Nd isotope plot of mafic igneous rocks, Southern Oklahoma Aulacogen. Evolved and primitive continental flood basalt boundaries (Condie, 2001). Mantle source compositions: EM1 (enriched mantle 1), EM2 (enriched mantle 2), and HIMU (high μ = high $^{238}U/^{204}Pb$) (Hart, 1984, 1988); N-MORB (Sun and McDonough, 1989). Subcontinental Lithosphere-SCL (McDonough et al., 1985). Glen Mountain Layered Series, Oklahoma (Lambert et al., 1988); Late Wichita diabase dikes, Oklahoma (Hogan et al., 1995; Hogan et al., 1996); Mill Creek diabase dikes (this paper).

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Stop 2. Carlton Rhyolite and diabase intrusions in the East Timbered Hills

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Note: Stops 2A and 2B are on private land and permission must be obtained to visit the outcrops. Stop 2C is within Turner Falls Park and is owned by the City of Davis. A fee may be charged to enter the park.

Location: Stops 2A and 2B. Entrance to road to radio towers is on west side of US Hwy 77 ~0.4 mi south of exit 47 off Interstate 35, Murray County, Oklahoma. The seven outcrops that make up Stop 2A are along or near the road to the radio towers in NE¼ sec. 1, T. 2 S., R. 1 E. The UTM coordinates of the top of Signal Mountain are 670037E, 3809929N. The traverse that constitutes Stop 2B is in the deep gully in S½ N½ NE¼ sec. 1, T. 2 S., R. 1 E. The UTM coordinates at the end of the gully are 670540E, 3809730N. Stop 2C is made up of five outcrops in SW ¼ sec. 36, T. 1 S., R. 2 E. and E½ sec. 35, T. 1 S., R. 2 E. The UTM coordinates vary. All of the Stop 2 outcrops are in the Turner Falls 7.5' quadrangle.

INTRODUCTION

Cambrian igneous rocks exposed in the East and West Timbered Hills in the western Arbuckle Mountains form the core of two structural culminations at the crest of the Arbuckle Anticline. These rocks consist primarily of extrusive units and felsic hypabyssal intrusions belonging to the Carlton Rhyolite Group and are overlain unconformably by clastic and carbonate sedimentary strata of the Upper Cambrian to Ordovician Timbered Hills and Arbuckle Groups. Diabase intrusions penetrate the rhyolite succession and represent the youngest phase of Cambrian igneous activity related to development of the Southern Oklahoma Aulacogen in the Arbuckle region. The igneous rocks in the West Timbered Hills have received only limited attention to date, but Eschberger (2012) recently completed a detailed study of the rhyolites and diabase intrusions exposed in the East Timbered Hills (ETH). Much of that new work is presented in Eschberger et al. (this guidebook), and Stop 2 provides an introduction to some of the important outcrops on which that work is based. Rhyolites in the Arbuckle Mountains have commonly been termed the Colbert porphyry following Reeds (1910). However, these rocks represent part of the largely buried volcanic assemblage that reappears in the Wichita Mountains (Denison, 1958; Ham et al., 1964) where the felsic volcanic rocks have been termed the Carlton Rhyolite, and we prefer to use the latter term for all Cambrian rhyolites in the region that are related to the Southern Oklahoma Aulacogen.

Stop 2 is divided into three main parts (2A, 2B, and 2C), the geological context and locations of which are shown in Figures 1, 2, 3, and 4. In the ETH, the Carlton Rhyolite primarily consists of two thick rhyolite flows dipping to the southwest that are separated by a succession of bedded rhyolitic volcaniclastic deposits (Figs. 1 and 3). These rocks are intruded by a series of hypabyssal rhyolite bodies that can be divided into four main types based on phenocryst content and groundmass appearance (Eschberger et al., this guidebook). Stops 2A and 2C are located in the interior of the upper rhyolite flow, whereas Stop 2B provides a cross-sectional view of the lower flow, the intervening bedded volcaniclastic strata, and the lower and middle parts of the upper flow. Outcrops of diabase intrusions and some of the felsic hypabyssal intrusions can also be viewed in the general areas of these stops, although the diabases are typically poorly exposed.

Stops 2A and 2C can be accessed easily by road, and instructive outcrops can be visited there without much walking. Stop 2B is a traverse that involves some strenuous, off-trail hiking on steep slopes in a rocky drainage. This traverse is best attempted in cooler parts of the year. During the warmer months, dense thickets of vegetation, including

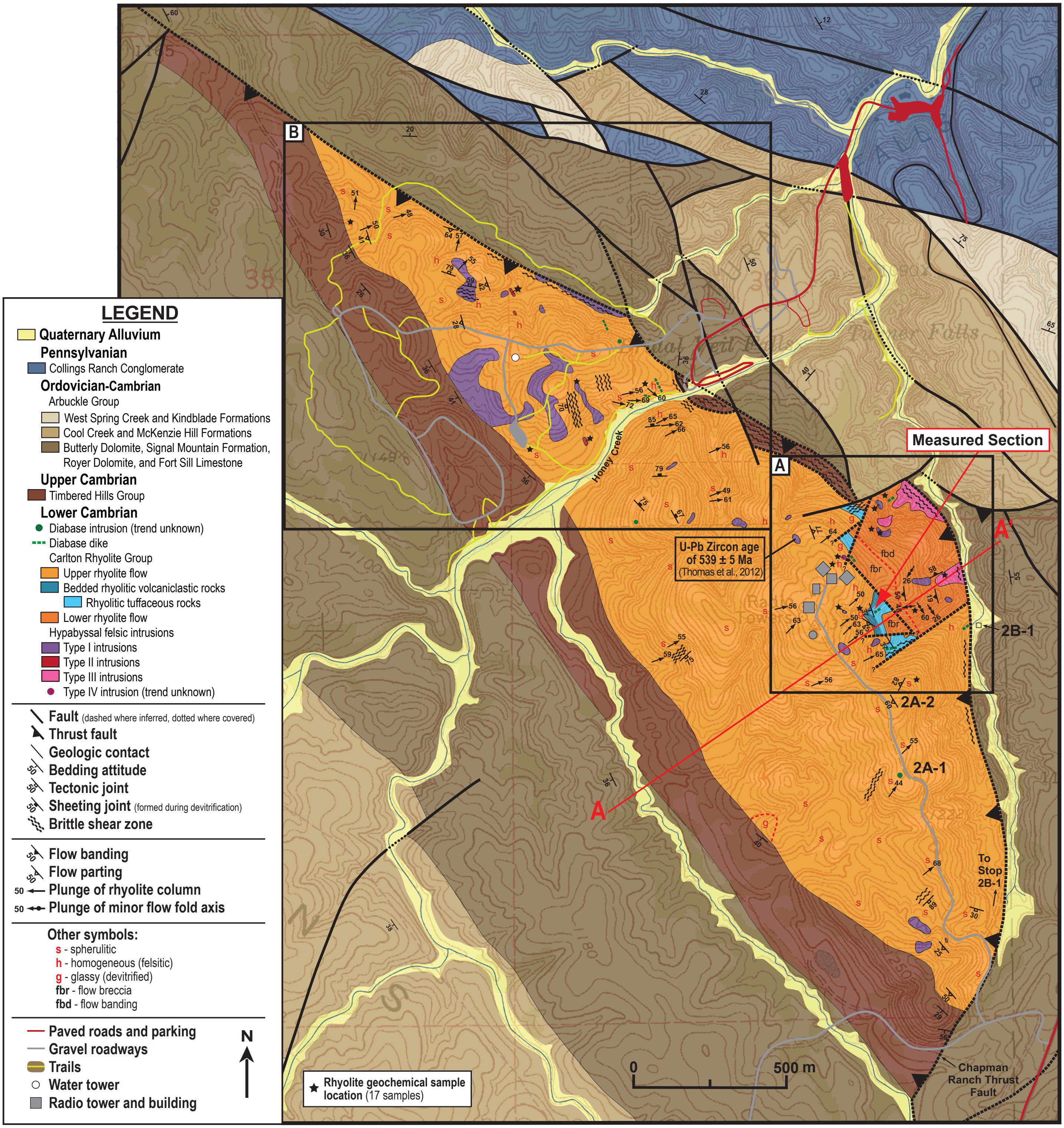

Figure 1. Geologic map of the East Timbered Hills. Field-trip stops 2A-1, 2A-2 and 2B-1 are indicated. Red dashed lines indicate boundaries between originally glassy and heterogeneous, spherulitic zones near top of upper rhyolite flow and between flow-brecciated and flow-banded parts of lower rhyolite flow. Line A-A' indicates location of cross section shown in Figure 3. Location of measured section shown in Figure 4 is also indicated. Geology of Upper Cambrian−Quaternary units is modified from Johnson (1990).

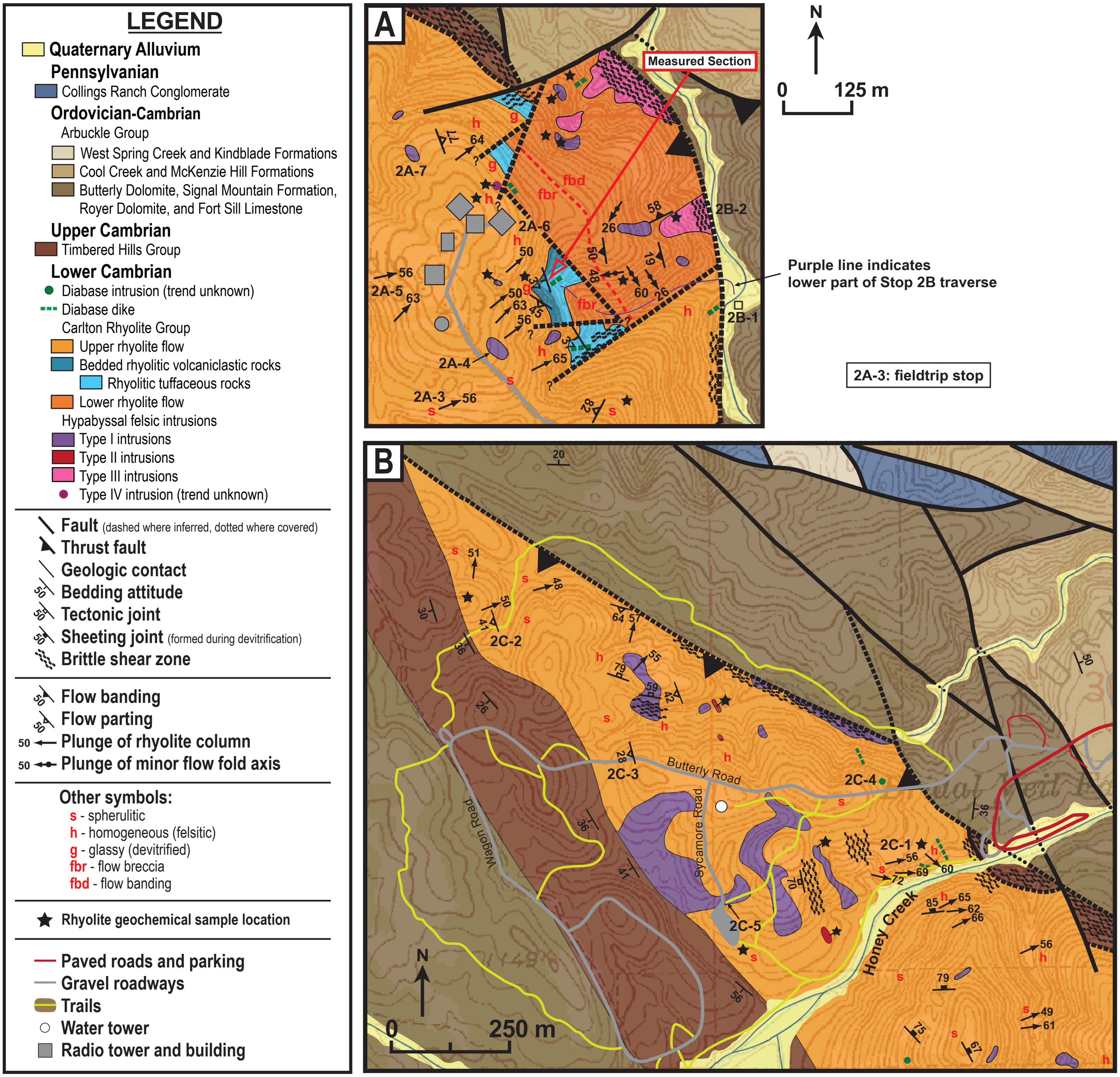

Figure 2. Closer views of areas labeled A and B in Figure 1, showing locations of all stops except for 2A-1 and 2A-2.

tangles of briars and abundant poison ivy, impede access to the outcrops. In the lower elevations, especially near water, one should also be on the lookout for wild pigs.

STOP 2A – ROAD TO TOWERS

After entering the Chapman Ranch, proceed along the road to the top of the peak. The first part of the road travels across carbonate rocks of the Arbuckle Group, which are overthrust by the rhyolites along the Chapman Ranch Thrust Fault (Fig. 1). Once the fault is crossed, the rest of the road to the top runs along outcrops within the interior of the upper rhyolite lava, which is ~600 m thick, making it the thickest flow so far documented in the Carlton Rhyolite Group. The flow can only be traced 3.5 km laterally before being truncated by faults or the unconformity with the Timbered Hills Group, but it may originally have been much longer. Throughout the upper flow, the principal phenocryst is alkali feldspar, with lesser amounts of quartz, titanomagnetite, and mafic silicates. The latter have been completely replaced by green clay ± hematite ± magnetite ± fluorite, but the shapes of these pseudomorphs suggest the primary phases were pyroxene and possibly fayalite. A simple cooling history after emplacement is recorded by a series of groundmass textures that are arranged in a consistent sequence vertically (Fig. 3). Microscopic features of these zones are discussed in Eschberger et al. (this guidebook).

Flow banding is absent in most of the upper flow, but different types of joints are commonly present. Columnar jointing is well developed (figs. 14A and 14B in Eschberger et al., this guidebook) and formed during initial cooling and contraction as the lava solidified. The columns typically plunge northeast, perpendicular to the base of the flow (fig. 13 in Eschberger et al., this guidebook). They are cut by sheeting joints (fig. 14C in Eschberger et al., this guidebook), which we interpret to have formed during subsequent contraction resulting from devitrification of glass. The term sheeting joint comes from Bonnichsen and Kauffman (1987) who used it to describe similar features in Miocene rhyolite lavas in the Snake River Plain. In the present case, the sheeting joints are typically spaced as much as several centimeters apart and have wedge-shaped terminations against adjacent joints. More closely spaced joints that are parallel to each other and impart a flaggy appearance to some outcrops are referred to as flow parting. As discussed in Hanson et al. (this guidebook), the origin of this type of jointing is unclear, but it may have formed when discrete planes of laminar shear developed in the lava during the final stages of flow. Flow parting in the upper flow is typically parallel to the base of the flow, although exceptions do occur. The difference between sheeting joints and flow parting is not obvious in cases where the sheeting joints become more closely spaced, and there are probably gradations between the two types of joints.

Several points of interest in the upper flow are accessible from the road leading to the top of the peak. At **location 2A-1** (Fig. 1), a small prospect pit visible in flat ground west of the road exposes part of a diabase intrusion, the shape and trend of which are unknown. The diabase contains plagioclase phenocrysts as much as 7 mm long that are highly altered to sericite and epidote, imparting a mottled appearance to the rock. A chemical analysis of the diabase is given in table 3 (sample 369) in Eschberger et al. (this guidebook). This diabase is texturally different from the other diabase intrusions we have mapped in the ETH, which lack large plagioclase phenocrysts.

At **location 2A-2**, outcrops on the east side of the road consist of rhyolite in the upper spherulitic zone of the flow (Figs. 1 and 3). The groundmass in this zone has a heterogeneous appearance in hand sample with abundant small (≤0.5 mm), white spherulites visible in a pink-gray groundmass. Also present at this location is well-developed flow parting spaced only a few millimeters apart. West of the road at **location 2A-3** (Fig. 2A), good outcrops allow examination of columns with roughly six-sided outlines in cross section that are overprinted by several sets of sheeting joints. Some of the sheeting joints are curviplanar, whereas others form fan-shaped arrays.

At **location 2A-4** (Fig. 2A), a small hypabyssal rhyolite intrusion is exposed a short distance east of the road. The intrusion is an example of the Type I intrusions described by Eschberger et al. (this guidebook). Type I intrusions differ from other felsic hypabyssal intrusions in the ETH, and from the upper rhyolite flow, in that they contain abundant dipyramidal quartz phenocrysts as much as 3.5 mm across in a microgranophyric groundmass that in some cases is barely phaneritic in hand sample and has a distinctive orange-pink color. These rocks in some cases could be termed microgranites, although the texture is extremely fine grained and rhyolite is probably a more appropriate term.

Proceed up the road and park vehicles near the towers. At **location 2A-5** (Fig. 2A) a short distance west of the towers, columns from 0.75 m to 1 m wide show little or no overprinting by sheeting joints. Outcrops on the slopes just east and northeast of the towers (e.g., **location 2A-6**, Fig. 2A) are within the most slowly cooled, felsitic interior

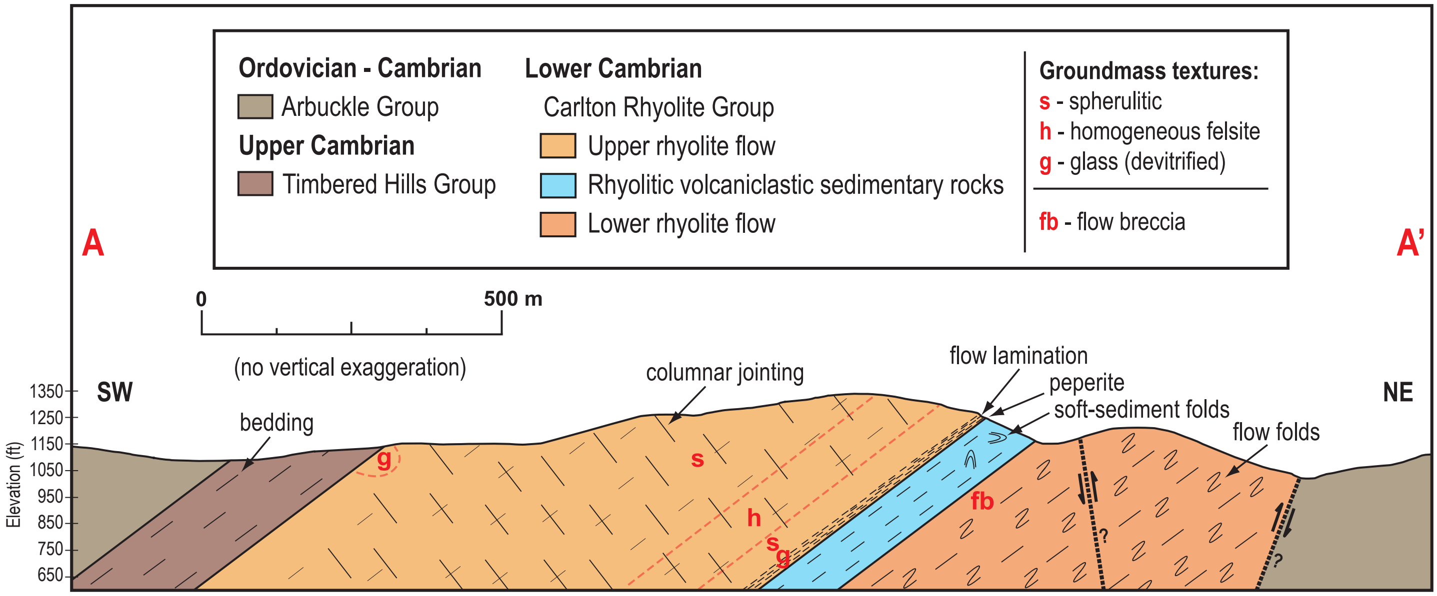

Figure 3. Cross section of East Timbered Hills; location shown in Figure 1. Hypabyssal felsic intrusions are not shown because their three-dimensional geometries are unknown. Boundaries between different textural zones in groundmass of upper rhyolite flow are shown schematically by orange dashed lines.

zone of the flow (Fig. 3), which is characterized in hand specimen by a homogeneous red-gray groundmass. In the vicinity of the towers, the interior zone grades upward into the upper spherulitic zone. At **location 2A-7**, a small Type 1 felsic intrusion crops out a short distance down the slope to the north-northwest of the towers (Fig. 2A). Thomas et al. (2012) obtained a U-Pb zircon age of 539 ± 5 Ma from this intrusion according to coordinates given for the sample location by those workers. This result is currently the only robust isotopic age available for the Carlton Rhyolite in the western Arbuckle Mountains.

STOP 2B – EAST CANYON

This stop is a traverse along a deep, roughly east-west-trending drainage that feeds into a tributary of Honey Creek (Figs. 1 and 2A). The traverse can be accessed either by going downslope from the parking area for the towers at the top of the peak or by proceeding up from the bottom. Some of the slopes in the drainage are steep and partly unstable, and for reasons of safety the traverse is probably not suitable for larger groups. It is also generally safer hiking up rather than going down the steep slopes. To start from the bottom, drive back down the road leading to the towers. Just east of the Chapman Ranch Thrust Fault, an unpaved road (which might not be suitable for driving) runs along the tributary to Honey Creek in this area. Walk along this road until it ends at a small concrete building, at **location 2B-1** (Figs. 1 and 2A). The traverse up the drainage begins a short distance north of this point.

To view an example of one of the Type III intrusions described in Eschberger et al. (this guidebook), proceed along the tributary of Honey Creek to **location 2B-2** (Fig. 2A). Type III intrusions are aphyric and have a barely phaneritic groundmass that is spherulitic in thin section. The intrusion at location 2B-2 forms well-polished outcrops along the stream bank and exhibits intense fracturing and pockets of fine-grained cataclasite resulting from brittle deformation along the Chapman Ranch Thrust Fault (fig. 17B in Eschberger et al., this guidebook). The outcrops along the stream bank are brick-red in color, but away from the fault the intrusion develops a pink-gray color that is more characteristic of this rock type.

The lower part of the steep, east-west-trending drainage that is the focus of the traverse crosses a faulted contact between the upper flow to the south and the lower rhyolite flow to the north. The fault is not exposed at this location, and its presence is inferred from outcrop relations higher up the slope to the west. The first good outcrops in the drainage are within the lower rhyolite flow. This flow is >300 m thick but its base is truncated by the Chapman Ranch Thrust Fault, so that its true thickness is unknown. Unlike the upper flow, the lower flow is aphyric and pervasively flow-banded and flow-folded. Amygdaloidal, spherulitic,

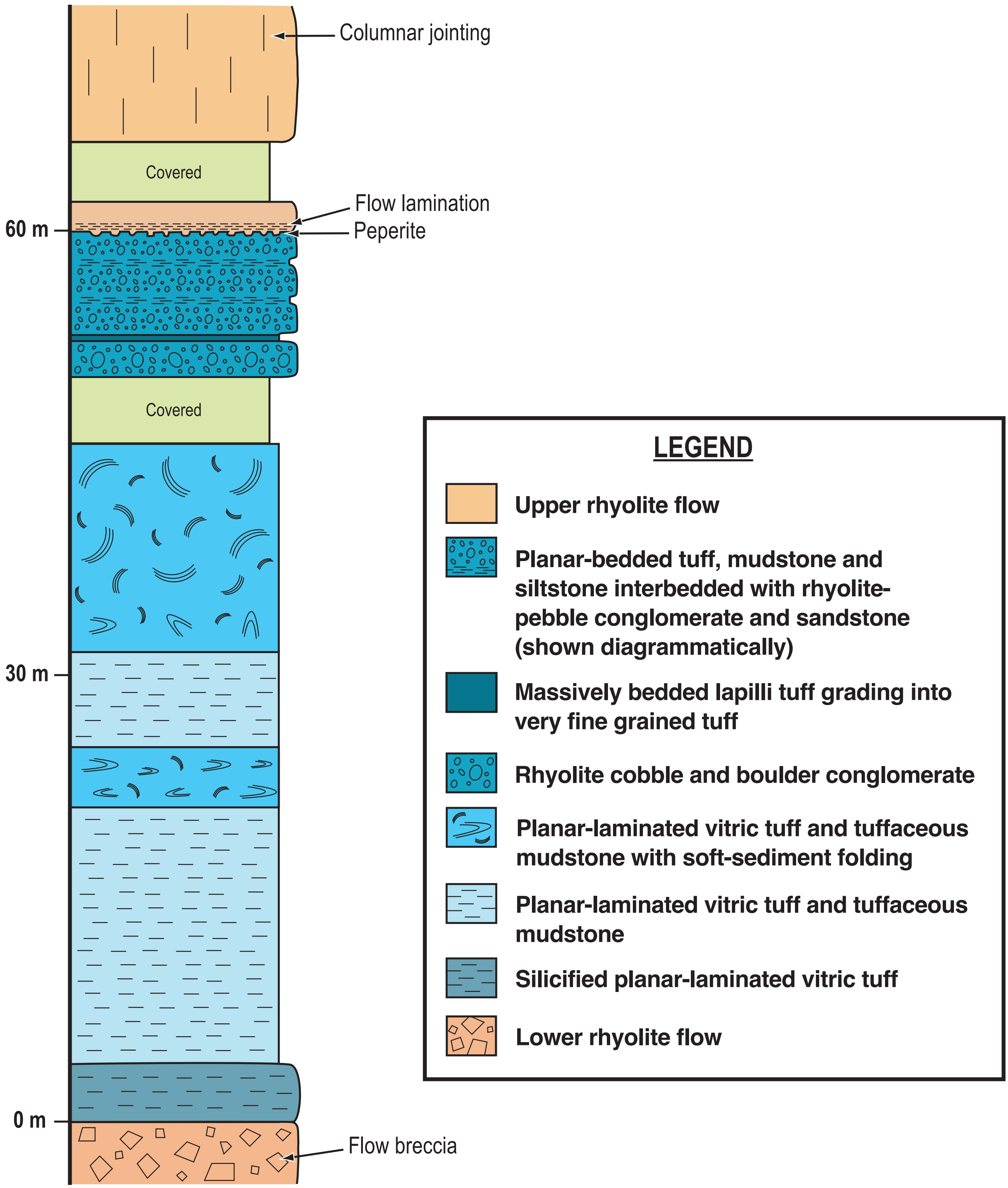

Figure 4. Measured section of bedded rhyolitic volcaniclastic sequence between upper and lower rhyolite flows. Location is shown in Figs. 1 and 2A.

and relict perlitic textures are visible in different bands in hand sample and in thin section (figs. 6, 7, 8A, and 8B in Eschberger et al., this guidebook). The spherulites record initial high-temperature devitrification shortly after emplacement. Subsequent hydration of the remaining glass formed perlitic texture, followed by slow, long-term devitrification of the hydrated glass at ambient temperatures to form a very fine grained quartzo-feldspathic intergrowth in the groundmass. The main, flow-banded part of the flow grades upward into a zone of flow breccia ~50 m thick in which chaotically arranged, internally flow-banded rhyolite clasts ≤1.5 m in length are present (figs. 8C and 8D in Eschberger et al., this guidebook). This is one of the best examples of flow breccia in the upper part of a flow that we have so far found in the Carlton Rhyolite, either in the Arbuckles or the Wichitas.

The flow breccia is overlain by a sequence of bedded rhyolitic volcaniclastic rocks 60 m thick (Fig. 4) that we interpret to have accumulated in a lacustrine setting. The volcaniclastic strata are offset by several faults (Fig. 2A). Although the geometry of these faults is not well understood, they have not significantly obscured the basic stratigraphic relations in the area. The lowermost 3.8 m of the sequence consists of dark, greenish-gray, ledge-forming rhyolitic tuff that shows pink and black mottling and is highly silicified. This tuff rests directly on the flow breccia at the top of the lower flow, although the contact in places is indistinct because the silicified tuff has a massive appearance somewhat like the lower flow. However, planar lamination is visible in places on weathered surfaces of the tuff, clearly distinguishing it from the underlying flow breccia. Rhyolitic tuff and tuffaceous mudstone exhibiting well-defined planar lamination make up most of the rest of the sequence and exhibit two zones of soft-sediment deformation with meter-scale soft-sediment folds (figs. 10 and 11A in Eschberger et al., this guidebook). The upper part of the sequence is dominated by planar-bedded rhyolitic volcaniclastic sandstone and pebble to boulder conglomerate, with some finer grained tuffaceous interbeds (Fig. 4).

The upper rhyolite flow rests directly on the bedded volcaniclastic rocks along a planar contact. A dark-gray to black, originally glassy chilled margin makes up the lower 40 cm of the flow and exhibits a delicate flow lamination (figs. 11B and 11C in Eschberger et al., this guidebook) that disappears upward. In places along the base, peperite formed where the lava underwent quench fragmentation and intermixing with underlying wet, unconsolidated tuffaceous sediments (figs. 12A and 12B in Eschberger et al., this guidebook). There is no evidence, however, for large-scale interaction of the rhyolite lava with external water, suggesting that the lake had largely dried up when the lava moved across it. The glassy base of the upper flow passes upward into the lower spherulitic zone (Fig. 3) that is ~40 m thick and has a similar heterogeneous appearance in hand sample to the upper spherulitic zone, with the same type of abundant, fine-grained spherulites. Still higher, this textural type grades into the homogeneous felsitic interior zone of the flow, which is exposed on the slopes leading up to the towers at the top of the peak. Columnar jointing perpendicular to the flow base is well exposed in the lower part of the flow above the bedded volcaniclastic rocks.

STOP 2C – TURNER FALLS PARK

Enter Turner Falls Park. Proceed past the turnoff for the parking lot and trail to Turner Falls and take the road branching to the southwest. This road allows access to numerous outcrops near or along the roads and trails in this part of the park. At **location 2C-1** (Fig. 2B), good exposures of the upper rhyolite flow can be seen along the foot trail that follows the northern bank of Honey Creek. These outcrops can be reached by taking the main paved road to its end in a large campground area, where parking is available on the side of the road. The rhyolite here is juxtaposed against deformed strata of the Timbered Hills and Arbuckle Groups to the east along a thrust fault that is part of the Washita Valley Fault Zone. Proceeding southwest along the trail, the first low outcrop is only a few meters from the side of the road and exposes rhyolite in proximity to the thrust fault. The rhyolite exhibits closely spaced tectonic fractures that grade into pockets of fine-grained cataclasite (fig. 5A in Eschberger et al., this guidebook), but this brittle deformation disappears a few meters farther west along the trail. Farther in this direction, cliffy outcrops on the north side of the trail are in the homogeneous felsitic interior zone of the flow. Geochemical sample 389 in table 3 in Eschberger et al. (this guidebook) comes from this location. The rhyolite here shows good columnar jointing with the long axes of the columns plunging 56º to 72º to the east or southeast (Fig. 2B). This plunge direction is different from the column long axes in most parts of the upper flow, which typically plunge to the northeast. The reason for this discrepancy is unclear, but it might be the result of displacement of this part of the flow along minor faults connected to the main thrust fault to the east.

The rhyolite cropping out along the trail is intruded by two diabase dikes (Fig. 2B), both of which are ~1 m wide. Geochemical samples 387 and 388 in table 3 in Eschberger et al. (this guidebook) come respectively from the dike closer to the start of the trail and the one farther to the west. To the north, above the cliffy outcrops just along the creek, the homogeneous felsitic interior of the upper flow grades upward into the upper heterogeneous, spherulitic zone. Flow parting is well developed in this area and tends to obscure the columnar jointing. The trail continues to the southwest along the north bank of Honey Creek all the way to the unconformity with the Upper Cambrian Reagan Sandstone at the base of the Timbered Hills Group (Fig. 2B), but the rhyolite is poorly exposed near the unconformity.

Outcrops higher up in the upper flow can be viewed at **location 2C-2** (Fig. 2B), which is a short distance off the Mountain Trail in the northwest part of the park. These outcrops are in the heterogeneous, spherulitic upper part of the flow and show columnar joints plunging northeast as well as crudely developed flow parting dipping southwest. Geochemical sample 375 in table 3 in Eschberger et al. (this guidebook) comes from similar rhyolite to the northwest, close to the unconformity with the Reagan Sandstone. The unconformity is visible a short distance farther southwest on the trail and is demarcated by the sudden change in vegetation from open grassy areas underlain by rhyolite to dense trees. The sandstone is well exposed past the start of the trees slightly farther along the trail and is a glauconitic, quartz-rich arkose or feldspathic litharenite with rhyolite lithic grains.

On Butterly Road at **location 2C-3** (Fig. 2B), an outcrop in the upper rhyolite flow shows pervasive flow parting dipping consistently to the southwest and locally crossed by closely spaced tectonic fractures. At **location 2C-4** farther east on Butterly Road (Fig. 2B), small core-stones of diabase can be seen in a campground on the north side of the road and extending down the slope from the campground a short distance to the east. The core-stones were released from spheroidally weathered diabase, but we have not been able to locate in situ outcrops of this body. Nonetheless, the core-stones provide reasonably fresh samples, and geochemical sample 386 in table 3 in Eschberger et al. (this guidebook) comes from this locality. To access **location 2C-5** (Fig. 2B), drive south on Sycamore Road from Butterly Road and park a short distance east of Sycamore Road at the start of a trail heading east. At this point, low outcrops reveal good examples of one of the Type I hypabyssal rhyolite intrusions described by Eschberger et al. (this guidebook) and also seen at location 2A-4 in the Chapman Ranch. As at that stop, abundant quartz phenocrysts are readily visible in an orange-pink groundmass. Close inspection with a hand lens should reveal a micrographyric groundmass texture. This outcrop also contains examples of lithophysae, a term which refers to typically relatively large spherulites that have grown out from a central gas cavity. In the present case, the lithophysae are as much as 1.5 cm across, and the central cavity is filled with secondary quartz and green clay. This is the only outcrop where we have seen lithophysae in any of the hypabyssal rhyolite intrusions in the ETH, but the presence of these gas cavities is consistent with a shallow level of emplacement.

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Stop 3. Mafic-felsic igneous breccia in the West Timbered Hills

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Location: Road to quarry is on the south side of OK Hwy 7 ~10 mi west of Davis, ~6.5 mi west of exit 55 off of Interstate 35, and 4 mi east of Hennepin. The entrance to the quarry is ~2 mi south of Hwy 7. The quarry (in Murray County, Oklahoma) occupies most of the E½ of sec. 10, T. 1 S., R. 1 W., Fox NE 7.5' quadrangle. Approximate UTM coordinates: 657610E, 3817690N.

INTRODUCTION

The West Timbered Hills in the Arbuckle Mountains remain the only significant area where exposures of volcanic rocks belonging to the Wichita Igneous Province have not been mapped in detail. That the area may contain important information bearing on the volcanic evolution of the Southern Oklahoma Aulacogen is illustrated by Stop 3, which is within a quarry operated by Hanson Aggregates, Inc., in the western part of the West Timbered Hills (Fig. 1). The quarry exposes a large mass of coarse-grained, polymict igneous breccia that contains chaotically mixed mafic and felsic clasts set within a fragmental matrix. The breccia mass appears to cut discordantly across extrusive rocks of the Carlton Rhyolite Group, although faulting has affected the contacts in places. No other examples of this type of breccia are known within the Wichita Igneous Province.

Uhl (1932) first described the breccia in the area now being exploited by the quarry, although he did not map its extent. Price et al. (1998) provided a description of the breccia exposed in the quarry and suggested that subsurface explosions driven by interactions between mafic magma and groundwater were involved in formation of the breccia. The breccia is located <1 km south of the Washita Valley Fault Zone, which represents a Cambrian rift-bounding fault that was reactivated as a thrust during Pennsylvanian inversion of the aulacogen (Ham et al., 1964). As noted by Price et al. (1998), proximity of the area to this major rift fault during Cambrian volcanism probably facilitated access of groundwater to shallow-level magma bodies, causing the explosive interactions. Eschberger (2012) carried out a detailed petrographic study of parts of the breccia, the results of which are discussed in Eschberger and Hanson (this guidebook), and the reader is referred to that paper for relevant photographs of features mentioned in the stop description.

STOP DESCRIPTION

Exposures in the quarry walls show that the breccia is unconformably overlain by the Upper Cambrian Reagan Sandstone and is intruded by or faulted against bodies of diabase (Figs. 2 and 3). The largest diabase intrusion is visible in the western quarry wall and is estimated to be ~200 m across (Fig. 3). Diabase dikes with widths of 1 to 2 m and variable orientations intrude other parts of the breccia. Much of the breccia appears to be massive, but tilted layering defined by variations in clast size and abundance is visible within the breccia in places in the quarry walls.

Visitors are not allowed to approach the walls because of safety considerations, but large pieces of the breccia can be examined on the quarry floor (Fig. 2). Our study of the breccia is based on a suite of samples collected from these loose pieces. Mafic clasts in the breccia include basalt and diabase, and felsic clasts include rhyolite and microgranite. The breccia is clast- to matrix-supported, and clasts range from angular to subrounded, with the largest examples being >1 m across. Abundant evidence for hydrothermal alteration is present in the form of veins containing carbonate, chlorite, epidote, and hematite (Price et al., 1998; Elmore et al., 1998). More than one episode of alteration affected the rocks, but paleomagnetic data show that an important part of the alteration occurred as the result of fluid flow during Pennsylvanian inversion of the aulacogen (Elmore et al., 1998).

In thin section, rhyolite clasts typically show spherulitic to felsitic textures of the same types that are present

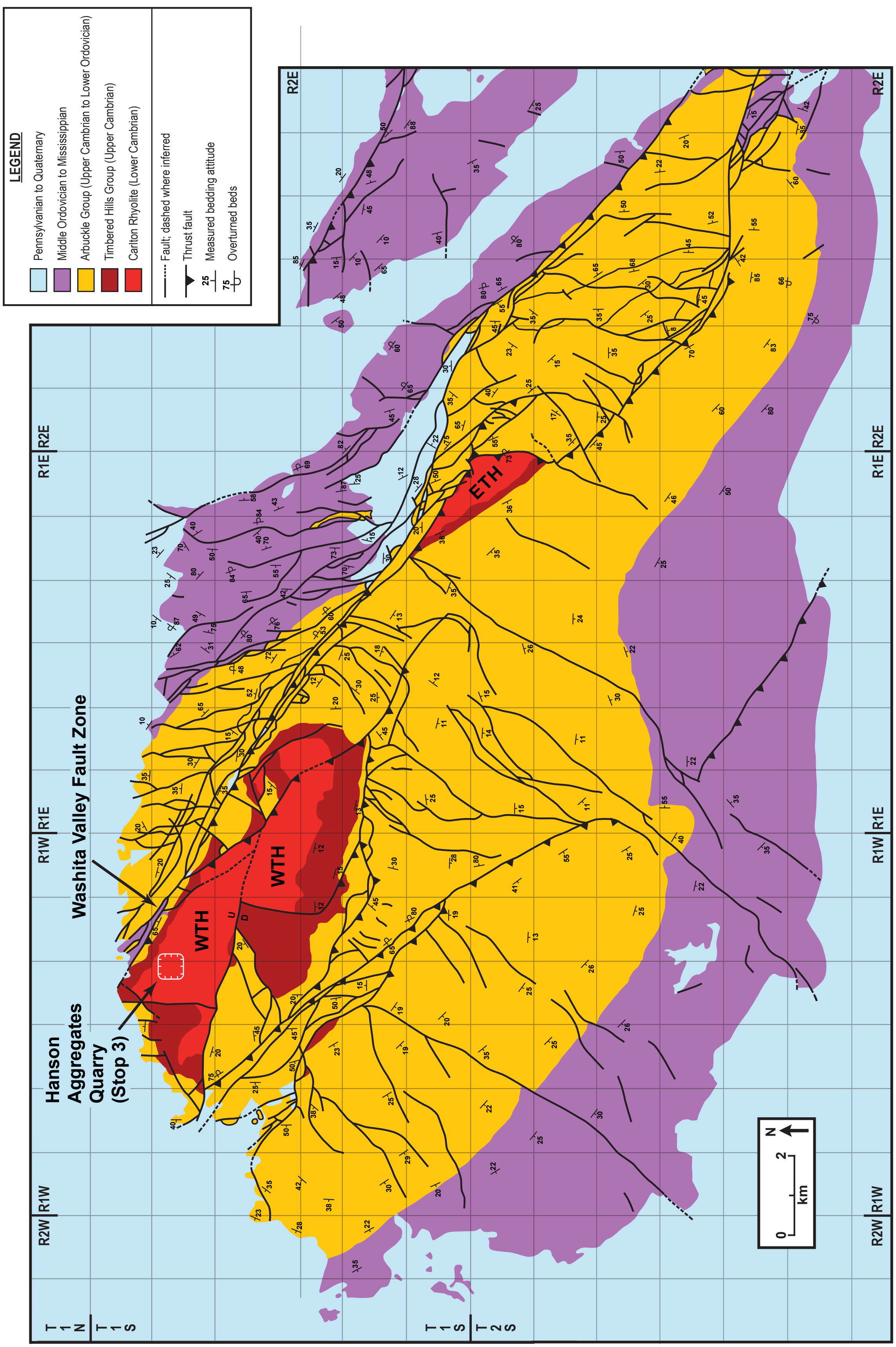

Figure 1. Geologic map of the western Arbuckle Mountains, including the West Timbered Hills (WTH) and the East Timbered Hills (ETH). Modified from Johnson (1990). Location of Hanson Aggregates Quarry (Stop 3) is indicated. WVFZ: Washita Valley Fault Zone.

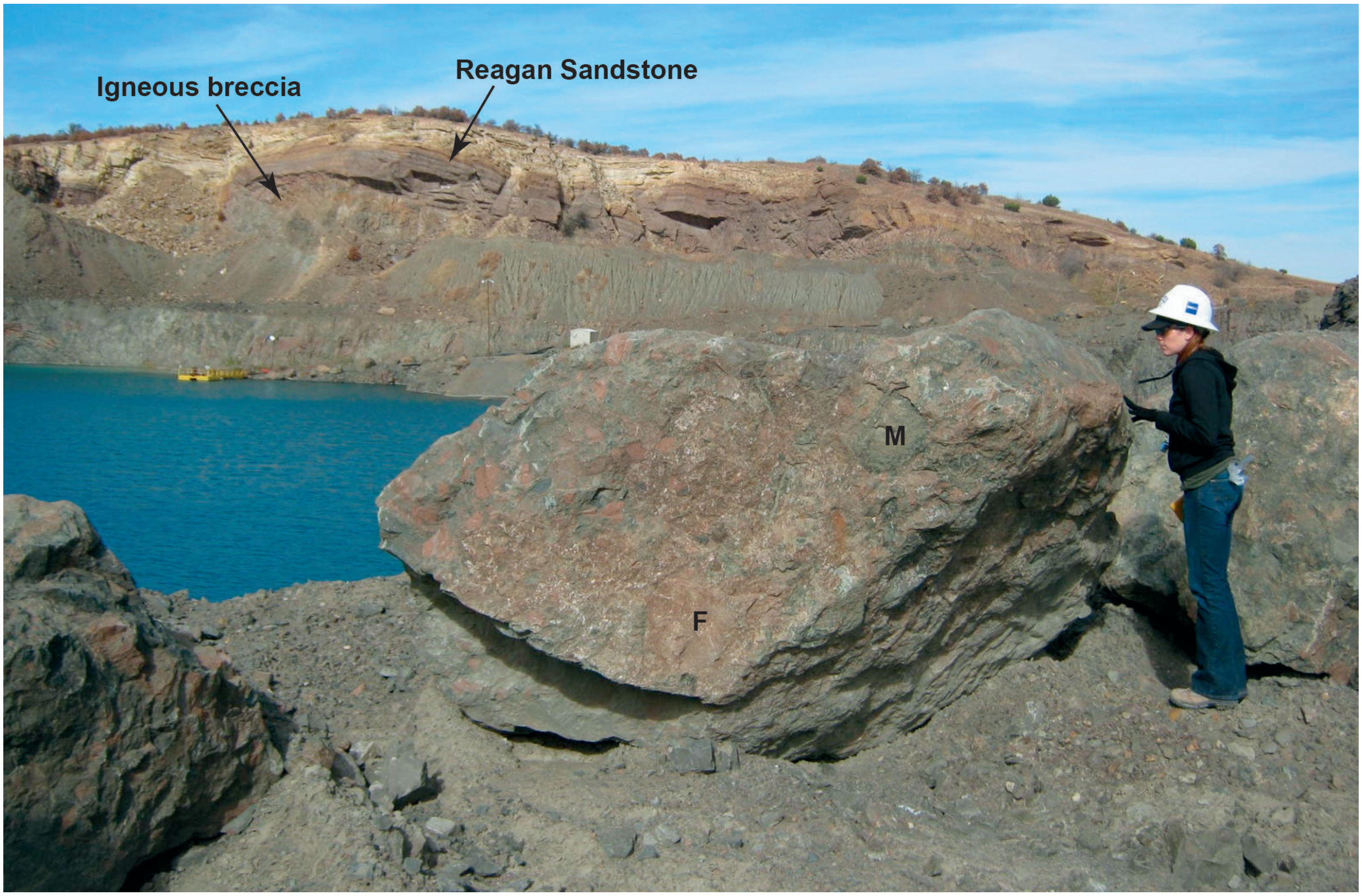

Figure 2. Igneous breccia exposed in loose pieces on quarry floor; representative felsic (F) and mafic clasts (M) are indicated. Unconformity between Reagan Sandstone and breccia is visible in background. First author for scale.

elsewhere in the Carlton Rhyolite, and tridymite needles (inverted to quartz) are common in the samples showing felsitic texture. Phenocrysts and glomerocrysts include plagioclase, alkali feldspar, and titanomagnetite, as well as mafic silicates showing varying degrees of alteration to green clay, carbonate, and epidote. Well-preserved augite is present in some samples, which is unusual for the Carlton Rhyolite, where the mafic silicates in almost all cases are completely replaced by secondary minerals. We have also identified aegirine or aegirine-augite in a few clasts, indicating an original peralkaline composition.

Microgranite clasts have phenocrysts and glomerocrysts of plagioclase, titanomagnetite, and variably altered augite. The groundmass is very fine grained but phaneritic and contains spherulites, tridymite needles (inverted to quartz), and interstitial micrographophyre. All of the microgranite clasts we examined have similar mineralogical contents and may have been derived from a single hypabyssal intrusive body. Chemical analyses of a rhyolite clast and a microgranite clast indicate very similar major- and trace-element compositions, pointing to a close petrogenetic relationship (Eschberger and Hanson, this guidebook).

Diabase clasts show intergranular, subophitic, and ophitic textures, and some contain plagioclase phenocrysts. In one clast, plagioclase crystals are aligned parallel to bands of magnetite grains (fig. 7A in Eschberger and Hanson, this guidebook), and we interpret this sample to represent a cumulate rock. Micrographophyre typically occurs in interstices between the main igneous minerals in the diabases, and a few clasts show larger segregations of felsic material. In the most striking example, the segregations are as much as ~8 cm across (fig. 6A in Eschberger and Hanson, this guidebook). Based on these features, we infer that some of the diabase clasts were derived from one or more intrusions large enough to undergo internal differentiation and segregation of low-density felsic melt.

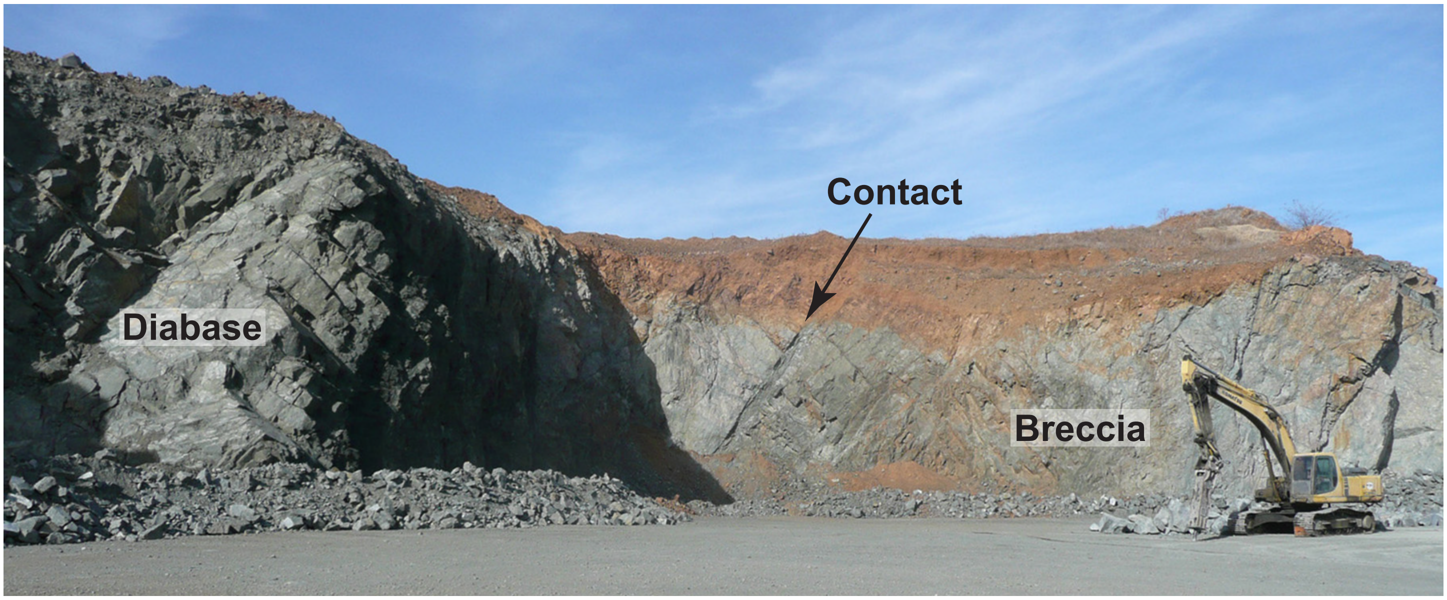

Figure 3. Massive diabase intrusion showing high-angle contact against igneous breccia.

Basalt lithic clasts are also visible in the pieces of breccia on the quarry floor, but we have not observed any volcanologically significant features in these basalt clasts on hand sample or outcrop scale. For example, no examples of fluidal bombs have been seen.

Textures of the breccia matrix are best seen on cut slabs and in thin section. The finer grained material between the coarse clasts consists partly of angular to subangular fragments of the same mafic and felsic rock types that make up the coarser clasts, together with loose crystals and crystal fragments released from these rocks. The crystal and lithic debris ranges in size down to irresolvable dust between particles in the matrix. Mafic material is generally dominant in the matrix, although it varies in amount. A significant amount of the mafic debris ≤5 mm across is seen in thin section to consist of altered sideromelane glass, as described in Eschberger and Hanson (this guidebook). Sideromelane is a special type of basaltic glass that is produced during rapid quenching of basaltic magma in contact with external water. The altered sideromelane fragments in the breccia matrix have shapes that vary from angular to fluidal. Vesicles occur in variable amounts, but clast margins are controlled by fracture surfaces rather than broken bubble walls. The abundance of sideromelane and the shapes of the fragments support the hypothesis of Price et al. (1998) that the breccia formed from explosive subsurface interactions between basaltic magma and groundwater. Sideromelane pyroclasts of this type are characteristic of phreatomagmatic eruptions in which magma fragmentation occurs by a combination of explosive release of magmatic volatiles and steam explosions driven by rapid heating of large volumes of water intermixed with the fragmenting melt (see references in Eschberger and Hanson, this guidebook). The apparent absence of bombs in the breccia may indicate that the phreatomagmatic explosions were sufficiently violent to completely disrupt the basaltic magma into small lapilli- and ash-sized particles.

Our model for the igneous breccia exposed in the quarry is illustrated in Figure 4. We interpret the breccia to fill the diatreme feeder conduit to a type of phreatomagmatic volcano known as a maar, in which the crater widens as it cuts down into bedrock as explosive activity continues (Lorenz, 1986). Rounding of some clasts is inferred to have occurred by repeated collisions between clasts within the conduit. Layering in some areas of the breccia could indicate that parts of the ejecta rim collapsed into the conduit (Fig. 4), as is commonly seen in other described phreatomagmatic diatremes (White and Ross, 2011). Based on the types of clasts in the breccia, the diatreme conduit cut through a succession of rhyolite lavas penetrated by hypabyssal microgranite and diabase intrusions (Fig. 4). Explosive activity in such a scenario would have been initiated when rising basalt magma encountered levels in the subsurface sufficiently rich in groundwater. If this interpretation is correct, the breccia exposed in the quarry represents the only known basaltic vent so far identified within the Wichita Igneous Province. However, basaltic phreatomagmatic deposits have been identified in cuttings

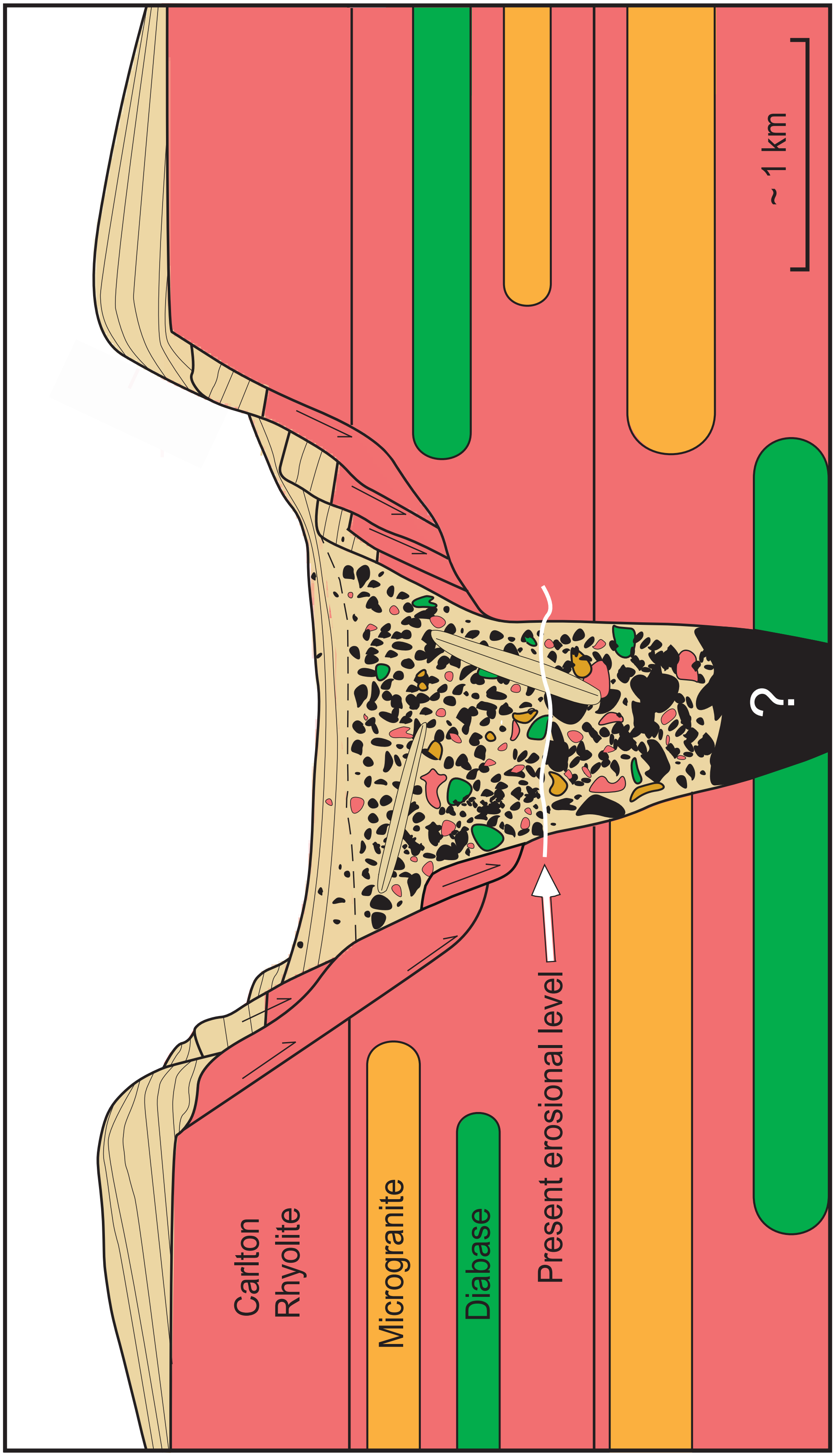

Figure 4. Model for formation of the igneous breccia as the fill of a diatreme feeder to a maar volcano, modified from Befus et al. (2009). Present erosional level is indicated by white line.

from several basement wells in the province, where they are associated in part with basaltic lavas (Ham et al., 1964; Puckett et al., this guidebook). Thus, a growing body of evidence suggests that explosive basaltic phreatomagmatism was important at times in the volcanic evolution of the Southern Oklahoma Aulacogen.

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Stop 4. Carlton Rhyolite and diabase intrusions in the Blue Creek Canyon area of the Slick Hills

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Location: On east side of OK Hwy 58 ~8 mi north of intersection with OK Hwy 49, Comanche County, Oklahoma. SW¼ SW¼ NW¼ sec. 13, T. 4 N., R. 13 W., Meers 7.5' quadrangle. UTM coordinates: 543225E, 3853240N.

INTRODUCTION

This stop provides an introduction to aspects of the Lower Cambrian Carlton Rhyolite Group and associated diabase intrusions where these rocks are exposed in the Slick Hills, north of the main mass of the Wichita Mountains. The area lies within the transpressional Frontal Fault Zone, which shows dominantly reverse offset with a component of left-lateral strike-slip displacement and was active during Pennsylvanian inversion of the Southern Oklahoma Aulacogen (McConnell, 1989; Donovan, 1995). During this deformation, the Meers Fault to the south (Fig. 1) juxtaposed the massive igneous core of the Wichita Uplift against strongly folded layered rocks to the north (Ham et al., 1964). Outcrops in the Slick Hills consist primarily of Carlton Rhyolite and unconformably overlying Upper Cambrian and Ordovician strata of the Timbered Hills and Arbuckle Groups, with well-bedded carbonate rocks of the Arbuckle Group showing the most intense folding (Donovan, 1986; McConnell, 1989). Farther north, the structural block represented by the Slick Hills is separated from the deep Anadarko Basin to the north by the Mountain View Fault (Harlton, 1963), which is present in the subsurface ~9 km north of the northernmost outcrops of Carlton Rhyolite at Zodletone Mountain (Fig. 1). The structural relief across the Frontal Fault System is impressive. Just north of the trace of the Mountain View Fault, geophysical evidence indicates that the Carlton Rhyolite is as much as 10 km deep (Buckey, this guidebook), and it must be deeper beneath the axis of the Anadarko Basin farther north.

The Carlton Rhyolite is exposed in three main areas in the Slick Hills, including Zodletone and Bally Mountains and the Blue Creek Canyon area (Fig. 1). Scattered smaller hills near some of these main outcrop areas provide additional rhyolite exposures that are too small to show on the scale of Figure 1. In most areas, the rhyolites are overlain with slight angular unconformity by the Upper Cambrian Timbered Hills Group (Donovan, 1986; Philips, 2002), which comprises the Reagan Sandstone at the base and overlying carbonate rocks of the Honey Creek Formation. These strata are succeeded by Cambrian and Ordovician carbonate rocks of the Arbuckle Group. In several places, paleohills of rhyolite project well above the general level of the unconformity into the Arbuckle Group, indicating the presence of significant erosional relief on the unconformity surface (Donovan and Bucheit, 2000).

We have mapped almost all the rhyolite exposures in the Slick Hills. The greatest exposed stratigraphic thickness of rhyolite (~2 km) occurs at Bally Mountain, but rhyolite flows in the Blue Creek Canyon area can be traced over a greater lateral distance (Fig. 2). As described in more detail in Hanson et al. (this guidebook), we have recognized at least 29 separate rhyolite flows in the Slick Hills outcrops, ranging in thickness to as much as 400 m. Individual flows tend to show a standard vertical sequence of textures and structures, as illustrated schematically in Figure 3. The complete sequence of zones is absent in many cases, but individual zones, where present, generally occur in the same predictable sequence. Upper and lower chilled margins to the flows are defined by originally glassy zones that have undergone hydration to form perlitic texture, together with alteration and devitrification of the glass. Well-developed flow banding and delicate flow lamination are present within the originally glassy zones and extend somewhat farther into flow interiors. Zones of abundant lithophysae consisting of spherulites cored by open gas cavities tend to form distinctive horizons along the inner boundaries of the glassy zones. Flow interiors consist of massive, homogeneous felsitic rhyolite that lacks any trace of relict glass. These felsitic zones are resistant to erosion and generally form peaks and ridges in areas of rhyolite outcrop.

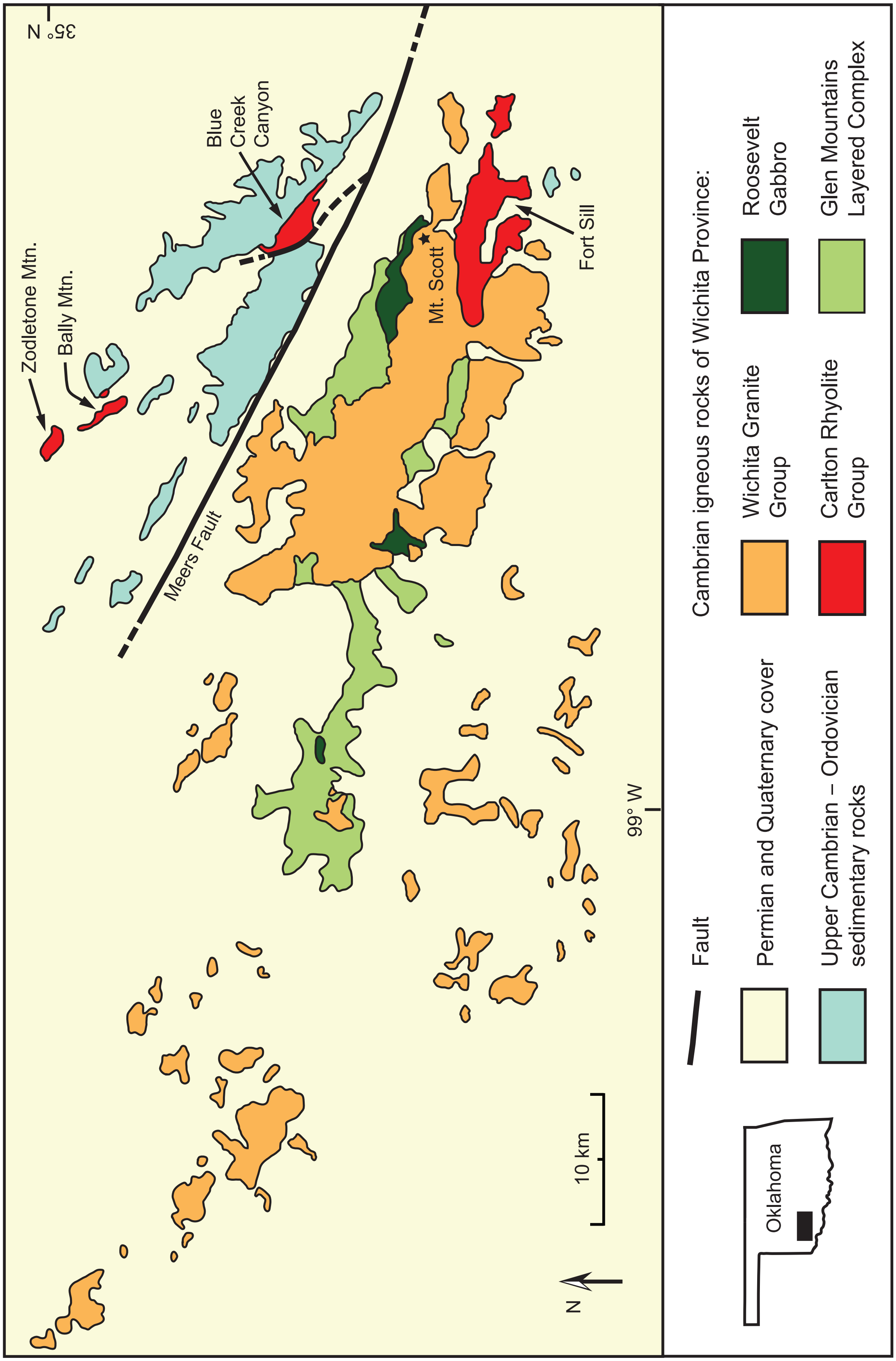

Figure 1. Simplified geological map of the Wichita Mountains, indicating location of the Blue Creek Canyon area within the Slick Hills. Modified from Powell et al. (1980) and Donovan (1995).

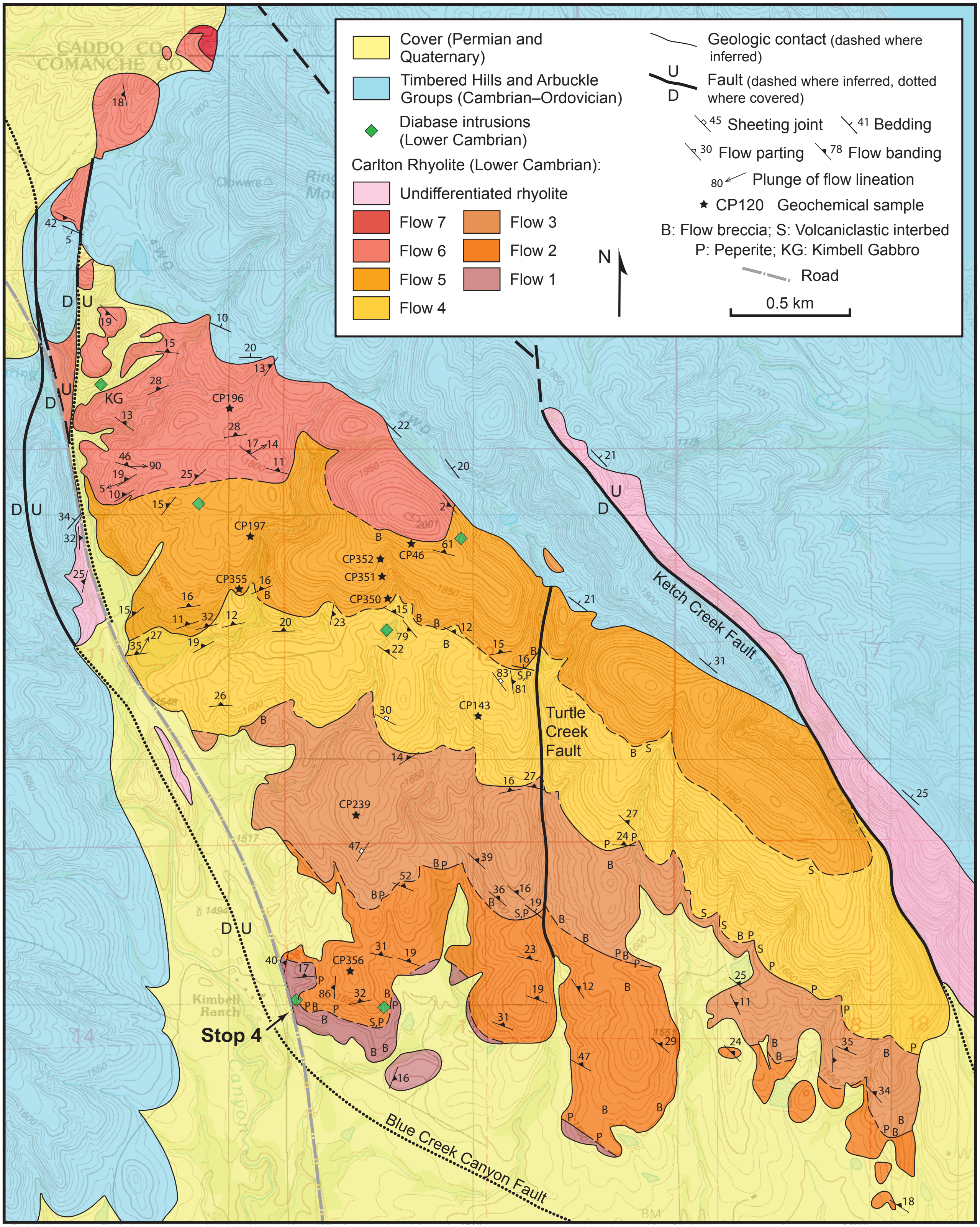

Figure 2. Geological map of the Carlton Rhyolite in the Blue Creek Canyon area, from Philips (2002); faults and Paleozoic sedimentary rocks are from Donovan et al. (1986) and McCall (1994).

In some cases, the flows rest directly on top of each other, but in other cases flows are separated by intervals of bedded volcaniclastic rock. The thickest such interval in the Slick Hills occurs at Bally Mountain, where a sequence of vitric ash-fall tuff, tuffaceous mudstone, rhyolitic sandstone and conglomerate, and polymict debris-flow deposits forms a sequence ~100 m thick that is inferred to have accumulated in a lacustrine setting (Hanson et al., this guidebook). In most cases, the volcaniclastic intervals consist of rhyolitic sandstone, vitric tuff, and tuffaceous mudstone and are <1 m thick. Discontinuous zones of peperite occur at the base of a number of the flows (Fig. 3) and developed when rhyolite lava underwent quenching, fragmentation, and intermixing with underlying wet, unconsolidated sediment as the lava flowed across the surface.

STOP DESCRIPTION

Stop 4 is at a roadcut on Highway 58 across from the Kimbell Ranch headquarters. The general geologic setting of the stop is described in Donovan et al. (1982, 1986). The highway runs near the trace of the Blue Creek Canyon Fault, which connects with the Meers Fault to the south and has thrust Carlton Rhyolite exposed to the east onto the Arbuckle Group to the west. The Blue Creek Canyon Fault has a displacement of ~900 m down to the west in this area (McCall, 1994).

We have mapped seven separate rhyolite flows in the Blue Creek Canyon area (Fig. 2), using criteria described above. The total stratigraphic thickness of rhyolite exposed in the area is ~1 km. The thickest flow (Flow 2 in Fig. 2) is 230 m thick. Areas of undifferentiated rhyolite are also present, and the original stratigraphic relations of those rocks to the mapped flows are uncertain. Some of the undifferentiated rhyolite within a structurally complicated zone marked by two splays of the Blue Creek Canyon Fault is unconformably overlain by the Honey Creek Formation. Absence of the Reagan Sandstone there indicates that the rhyolite outcrop represents one of the paleohills developed on the pre-Reagan unconformity (Donovan et al., 1986). Undifferentiated rhyolite also forms a long sliver east of the Ketch Creek Fault, which is another structure that developed during Pennsylvanian inversion of the aulacogen and has a displacement of ≤150 m down to the west (Donovan et al., 1986). The Turtle Creek Fault cuts the main rhyolite sequence but stops at the unconformity with the overlying sedimentary strata (Donovan, 1995), indicating that the fault predates the Upper Cambrian Reagan Sandstone. Evidence of brittle shearing occurs along the fault, including fault breccia and quartz veining (Marchini, 1986). However, our mapping reveals no evidence for displacement of rhyolite flow contacts across the fault, which must represent a fairly minor structure.

The roadcut at Stop 4 reveals the upper part of the lowest rhyolite flow exposed in the Blue Creek Canyon area. This flow is at least 50 m thick. Its base is covered, but relict perlitic texture is abundant in the southernmost outcrops of the flow, suggesting that these outcrops expose parts of the lower, originally glassy chilled margin. If so, most of the thickness of the flow is exposed. In the roadcut the rhyolite shows flow banding (Fig. 4) with variable attitudes and contains 15 to 20 % alkali feldspar and plagioclase phenocrysts in a somewhat heterogeneous groundmass that approaches a felsitic texture. Both feldspars are pink in hand sample. The lack of obvious quartz phenocrysts is typical of many of the rhyolites in the Slick Hills, although they are visible in minor amounts in some of the flows in the Blue Creek Canyon area. Lithophysae appear higher in this flow beneath an originally glassy chilled margin. The contact with the overlying flow is defined, in part, by a discontinuous zone of peperite, in which the overlying rhyolite has interacted with planar- and cross-laminated fine-grained volcaniclastic sandstone and very fine grained gray-green vitric tuff.

The rhyolite at the roadcut is intruded by a vertical diabase dike ~1 m across that strikes N70E (Fig. 5). The interior of the dike shows typical diabasic texture which grades into aphanitic basalt along the chilled margins. Amygdules as much as 1 cm wide in both the interior and the chilled margins are filled with dark green clay (DeGroat et al., 1995). This dike is representative of a large number of diabase intrusions, including dikes, sills, and transgressive sheets, that cut all other units of the Wichita Igneous Province in the Wichita Mountains and have commonly been referred to as the “late diabases” (e.g., Gilbert, 1983; Hogan and Gilbert, 1998). They are generally poorly exposed and in many cases are visible only in roadcuts or quarries (e.g., Price, Stop 5, this guidebook). The dike at the present stop is a case in point and does not crop out past the roadcut. About ~370 m to the east, diabase is exposed in two small prospect pits a few meters apart. This diabase has markedly different trace-element contents from the dike exposed in the roadcut, indicating that intrusion of distinct batches of mafic magma occurred in a limited area here (DeGroat et al., 1995).

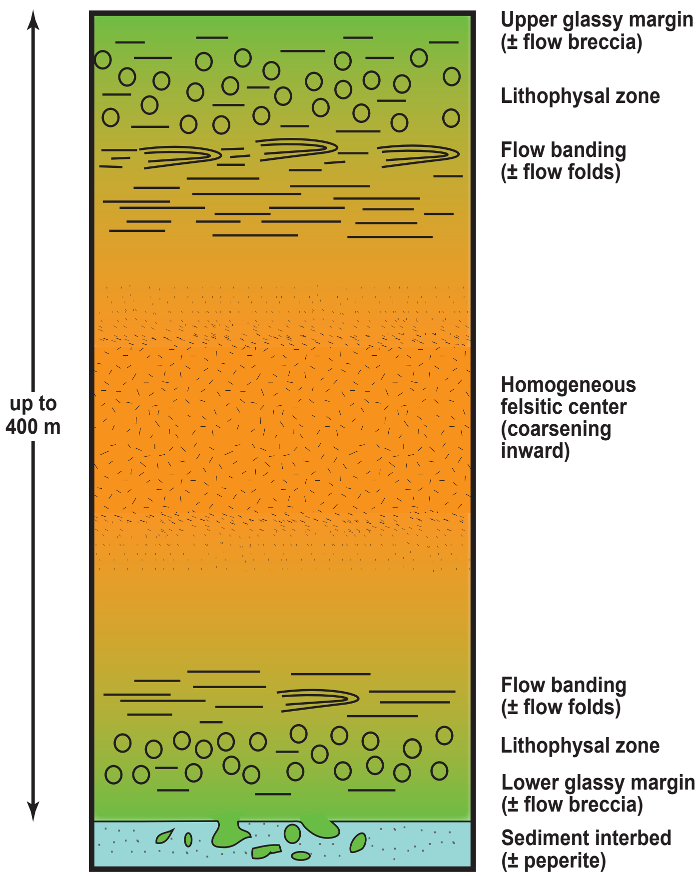

Figure 3. Generalized vertical zonation in Carlton Rhyolite flows exposed in the Slick Hills.

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Figure 4. Flow banding in rhyolite at Stop 4. Comb is 12 cm long.

Figure 5. Diabase dike intruding rhyolite at Stop 4.

Stop 5. The Diabase dikes intruding the Mount Scott Granite at Lake Elmer Thomas Dam, eastern Wichita Mountains

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Location: At end of short access road to Lake Elmer Thomas Dam south off of OK Hwy 49 ~0.1 mi west of Wichita Mountains National Wildlife Refuge boundary, ~7.2 mi west of exit 45 off of Interstate 44, and ~1.7 mi east of intersection of Hwy 49 and road to top of Mt. Scott (Stop 5, this guidebook), Comanche County, Oklahoma. SW¼ NE¼ SE¼ sec. 13, T. 3 N., R. 13 W., Mt. Scott 7.5' quadrangle. UTM coordinates: 544488E, 3843042N.

INTRODUCTION

Driving west through Medicine Park on Oklahoma Highway 49, one can see the imposing edifice of a dam closing a narrow canyon between two rocky hills. The dam impounds Little Medicine Creek to form Lake Elmer Thomas, a recreational reservoir that straddles the boundary between the Wichita Mountains Wildlife Refuge and the Fort Sill Military Reservation. The road to the dam top ends at a long defunct quarry. The Cambrian Mount Scott Granite is well exposed here, and two thin diabase dikes are exceptionally revealed along the floor and wall of the quarry at the western end.

Diabase (subvolcanic basalt) dikes cross-cut the granite here and elsewhere. These are similar in composition and structure to those found in the Arbuckle Mountains seen at Stop 1, 155 km to the east-southeast. Similar dikes demonstrably intrude all other igneous units in the Wichita Mountains, and older granite and rhyolite terrane in the Arbuckle Mountains, but not the unconformably overlying Reagan Sandstone or younger strata. These were commonly once grouped as "Late Diabase," a name suggesting an origin in the final throes of igneous activity associated with the Southern Oklahoma Aulacogen (SOA). Price et al. (2012), and prior work cited therein, suggests this site indicates SOA diabase can be *not-so-late*. They suggest "Diabase" as the appropriate lithodemic unit, consistent with recent work showing close temporal and spatial relationships between some of the felsic and mafic magmas in the SOA (Hames et al., 1998; Hogan et al., 1998; Wright et al., 1996).

The quarry at Lake Elmer Thomas Dam provides exposure of this Diabase unit, and of the Mount Scott Granite that it intrudes, and insight into the timing and nature of the intrusion of both units. However, the locale's accessibility is its greatest attribute. The quarry is just south of OK 49, 8.5 miles (13.7 km) west from I-44. A gravel road that leads to the quarry, open during daylight hours, intersects the highway just 0.3 miles (0.5 km) east of where the highway crosses into the Refuge. The gravel road terminates at the small parking area in a quarried site by the concrete dam. Please note that the quarry is on the Wichita Mountains Wildlife Refuge, a federal facility with rules similar to those of National Parks: do not collect samples or otherwise deface the rocks.

The following description is largely compiled from Price et al. (2012). Hogan et al. (1998) provided the insights regarding magmatic pressure of intrusions and dike and pluton geometry. Curious readers are directed to these resources for further details.

OVERVIEW AND REGIONAL STRATIGRAPHY

The quarry is carved into a rocky knob of granite (Figure 1) similar to many of the nearby hills near the eastern end of the granite exposures in the Wichita Mountains. The rock here is Mount Scott Granite, an alkali-feldspar granite characterized by distinct ellipsoidal feldspar phenocrysts and by mafic enclaves. The ellipsoidal feldspars (ovoids) are texturally complex phenocrysts with dark-gray perthitic cores of weakly ternary composition, commonly overgrown by an inner rim of plagioclase that is in turn mantled by red alkali feldspar with inclusions of quartz (Price et al., 1996). A variably granophyric matrix surrounds these

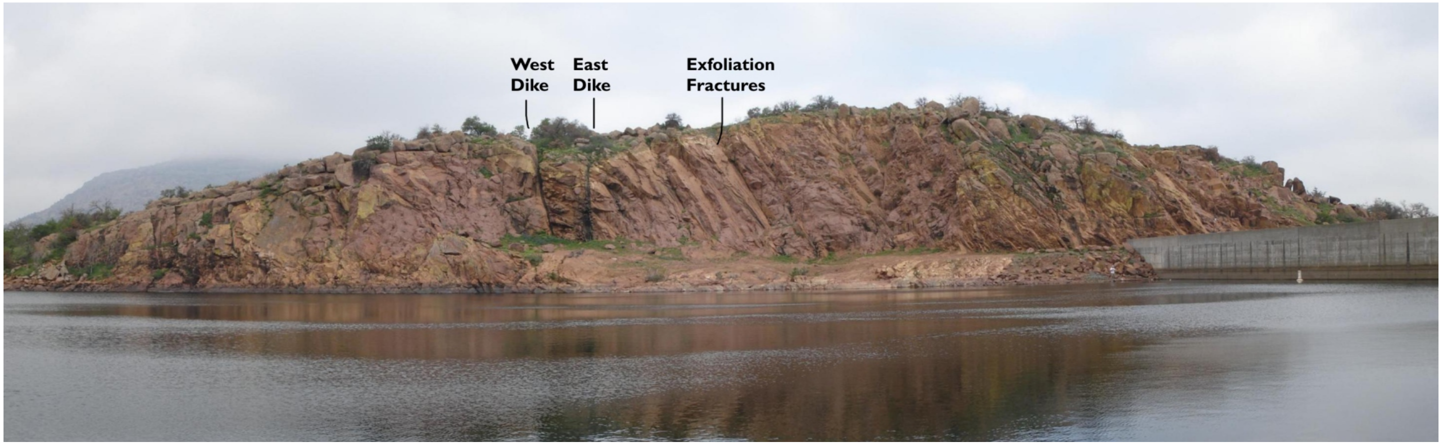

Figure 1. Panoramic photo of the quarried area and Lake Elmer Thomas and Dam looking north, Two diabase dikes cut the Mount Scott Granite. The granite exhibits exfoliation fractures. Mount Scott, on the left side of the frame, is partially shrouded by low cloud cover. Reproduced from Price et al. (2012).

ovoid alkali feldspar phenocrysts. The enclaves are clusters of abundant hornblende and biotite.

The Mount Scott Granite exposures are far from limited to the eastern Wichita Mountains – outcrops mark the southern shore of Lake Tom Steed, 50 km to the west. With a roughly north-south width of 17 km and a thickness of about 0.5 km, the Mount Scott Granite is easily the best exposed of the aulacogen's intrusive felsic rocks, the Wichita Granite Group. More remarkably, the Mount Scott Granite is compositionally homogeneous over this extent and exhibits only minor mineralogical and textural variation (see Price, this guidebook).

Igneous materials

The igneous stratigraphy of the Wichita Mountains shown in Table 1 is based on Powell et al. (1980), Myers et al. (1981), and Price (1998) and modified from Price et al. (2012). In addition to the Mount Scott Granite and Diabase found here, this location is proximal to the Medicine Park Granite and the Rush Lake Granite, two other Wichita Granite Group units that are demonstrably consanguinious with the Mount Scott Granite (see Price, this guidebook). Each are exposed within 4 km to the east in the hills underlying Medicine Park. The Rush Lake Granite is also exposed further west (Stop 7). The Carlton Rhyolite is found adjacent to the southern shore of the lake, 1.5 km to the southeast.

Felsic rocks dominate the nearby geology, but two members of the Raggedy Mountains Gabbro Group are exposed to the north-northwest. These share contacts with the Mount Scott Granite but are geochemically and mineralogically distinct from each other and the Diabase. The Glen Mountains Layered Complex (GMLC) is a series of stratified anorthosites, troctolites, and gabbros, similar to other large mafic complexes like the Bushveld of South Africa, the Bjerkreim-Sokndal in Norway, and the Stillwater Complex in Montana. The GMLC is the oldest exposed unit in the Wichita Mountains and predates the exposed felsic rocks. This regionally extensive, deep-seated plutonic body was unroofed prior to the onset of the exposed felsic activity. The Roosevelt Gabbros, five geographically separate plutons of hydrous (biotite-bearing) plutonic rock, are the second-most voluminous mafic material exposed in the Wichita Mountains. These were once thought to be distinctly older than the felsic magmatism, but recent work indicates they are contemporaneous with some of the granites (Hames et al., 1998; Hogan et al., 1998; Price et al., 1998; Wright et al., 1996).

With the exception of the Diabase, felsic rocks in the Wichita Mountains overlie the mafic ones. The lowest part of the Carlton Rhyolite directly overlies the eroded surface of the GMLC. As subsequent rhyolitic eruptions thickened the uppermost crust, the Carlton-GMLC boundary became a structurally weak zone that permitted intrusion of felsic sheet plutons. The Wichita Granite Group members each subhorizontally intruded the crust along the horizon between the older mafic rocks and the Carlton Rhyolite Group. These Wichita Granite Group bodies are tabular plutons, emplaced at relatively shallow depths and corresponding low lithostatic pressures of ~50 MPa (Hogan and Gilbert, 1998). Each member of the Wichita Granite Group is defined by textural and mineralogical features that are

<table>
<tr><td colspan="3">Table 1. Igneous Stratigraphy of the Wichita Mountains
All units are Early Cambrian, but some relative ages are not known
Modified from Price et al. (2012)</td></tr>
<tr><td>Diabase</td><td colspan="2">Basaltic dike series that cuts all the units below but whose ages span much of the sequence</td></tr>
<tr><td>Carlton Rhyolite Group
Thought to predate and span the granite ages</td><td colspan="2">Geographic Sections
Bally Mountain
Blue Creek Canyon
Fort Sill
Davidson Metarhyolite</td></tr>
<tr><td>Cold Springs Breccia
Otter Creek Microdiorite</td><td colspan="2">Fine-grained diorite mixed with leucogranite</td></tr>
<tr><td>Wichita Granite Group</td><td>Eastern Wichita Mountains
Quanah Granite – C*
Cache Granite – F
Saddle Mountain Granite – F, MSP**
Mount Scott Granite – F, MSP
Rush Lake Granite – F, MSP
Medicine Park Granite – F, MSP</td><td>Western Wichita Mountains
Reformatory Granite – C
Lugert Granite – F
Long Mountain Granite – F
Coopertown Granite – F
Headquarters Granite – F</td></tr>
<tr><td rowspan="2">Raggedy Mountain Gabbro Group</td><td colspan="2">Roosevelt Gabbros
Iron Mountain Gabbro
Mount Baker Gabbro
Glen Creek Gabbro
Sandy Creek Gabbro
Mount Sheridan Gabbro</td></tr>
<tr><td colspan="2">Glen Mountains Layered Complex
(previously divided into the K, L, M. N zones but revised to POc, POAc, PAc, Pc cycles)
oldest of the exposed igneous units</td></tr>
<tr><td colspan="3">*C is coarser-grained granite, F is finer-grained granite.
** MSP is part of the Mount Scott Intrusive Suite, see Price (this guidebook)</td></tr>
</table>

easily noted in the field. They are further segregated by geographic occurrence: those of the near-continuously exposed eastern Wichita Mountains versus those inselberg exposures in the west. The granites are A-type, within-plate granite. They are broadly similar in chemical composition but exhibit subtle variations. These compositional differences and variations in cooling regime also produced distinct textures and mineral assemblages. Early workers were quick to note that granophyric texture dominates many of the granites (see Ham et al. (1964) and references therein). Hogan et al. (2000) grouped the granites into two textural classes: finer-grained and coarser-grained; these are denoted for each unit by “F” and “C” on Table 1. The plutons of the Wichita Granite Group were likely intruded within a short time interval, but intrusive contacts suggest that the finer class is older. Mount Scott Granite is a finer-grained granite dated at 534 ± 1.5 Ma (Wright et al., 1996) and is one of the older granites in the eastern Wichita Mountains. The Mount Scott has the largest mapped outcrop and most continuous exposure of all the Wichita Granite Group.

The SOA rocks are cut by dikes of tholeiitic basalt with a diabase texture. Whereas the dikes cut the older granite and rhyolite terrane as exposed in the Arbuckle Mountains, no occurrences have been noted in the Upper Cambrian sedimentary units in either the Wichita or the Arbuckle Mountains. Because Diabase cross-cuts all of the exposed SOA rocks, earlier investigators reasonably assumed the Diabase to be the last recorded igneous activity of the rift system. However, recent work has shown that the initial intrusion predates the later coarse-grained granites and continued throughout much of the remaining igneous history of the Wichita Mountains (Price et al., 2012). With the GMLC and the Roosevelt Gabbros, these Diabase dikes represent a continuing process of basaltic magmatism in the SOA.

OUTCROP DESCRIPTION

Joints

The quarry walls are marked by curvilinear fractures or “exfoliation joints.” These are seen at the east end of the main quarry as roughly parallel, concentric fractures that generally strike 025° and dip 43° southeast. The fractures curve to subhorizontal attitudes at the western end of the main quarry. The fracture geometry is typical of unloading in granite bodies, deformation resulting from decreasing vertical stress due to overburden removal. Such fractures typically develop parallel to the exposed surface (Holtzhausen, 1989), indicating that the steeply dipping fractures at the eastern end of the hilltop are associated with the excavation of Little Medicine Creek. Sets of exfoliation joints in the Wichita Granites are likely to have developed at different times in response to cycles of burial and exhumation. Much of the current topography is superimposed on prominent topographic surfaces formed during Permian exposure (Stop 7), so the orientation of exfoliation joints may reflect a Permian topographic surface as opposed to a modern one.

The exfoliation joints and other prominent fractures are open (Mode I), permeable fractures in granite. In this area, fluid movement and water-rock interactions along fractures coated these features with clays, hematite, quartz, manganese oxides, and calcite. Price et al. (1998) documented alteration of primary magnetite to hematite (martite) in the Mount Scott Granite as a result of fluid movement along fractures to a depth of at least 20.5 m. Manganese-oxide staining, locally present as a thin coating along channels down the main quarry wall, attests to ongoing, although less substantial, fluid/rock interaction and fracture mineralization.

Mount Scott Granite

This stop contains noteworthy exposures of unweathered Mount Scott Granite. The fresh surfaces on the quarry walls and floor and on quarried boulders reveal key details. The two defining characteristic features of the granite are easily observed here: gray ovoid feldspars and mafic enclaves (Merritt, 1965). The characteristic ovoid feldspars are largely microperthites, typically elliptical in section, and set in a matrix of quartz and potassic alkali feldspar (Figure 2). These phenocrysts reflect a period of early crystallization of the magma at a ponding depth of 7 to 8 km, corresponding to pressures of 200 MPa (Hogan and Gilbert, 1995). Following initial crystallization, ascent decompression induced chemical resorption and produced plagioclase mantles, resulting in the ovoid shape and rapakivi texture (Price et al., 1996). Phenocrysts here generally exhibit thinner plagioclase rims than those seen at other localities. The rock matrix here is moderately granophyric, with growth dominantly radiating from the ovoid feldspars.

Although not optically apparent, electron-microscope cathodoluminescence (CL) and electron microprobe analysis reveal that the larger quartz phenocrysts are distinctive from granophyric and other, smaller quartz, as described in Price (this guidebook) and in Price et al. (2012), indicating pre-emplacement crystallization of quartz phenocrysts. The quartz exhibits rounded cores of low-intensity blue CL

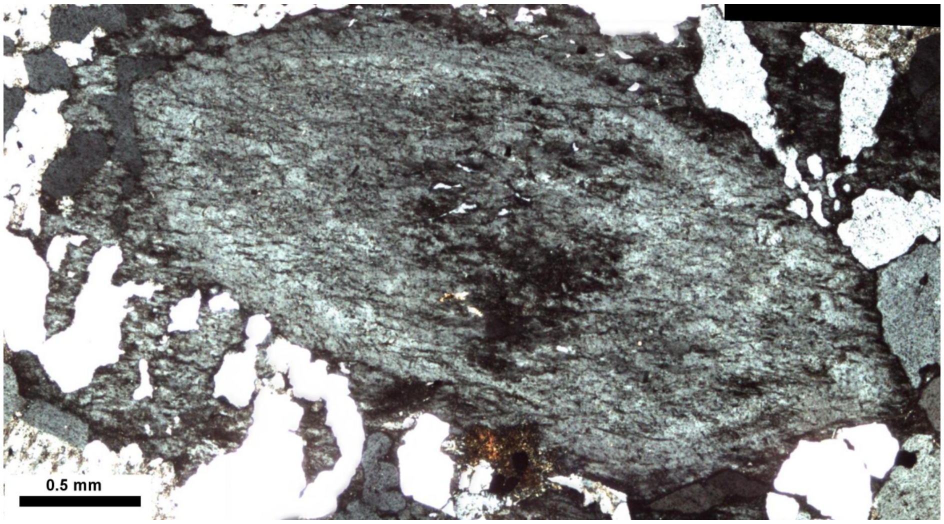

Figure 2. Ovoid alkali feldspar in matrix of quartz and feldspar in cross-polarized light. Note perthitic texture within the ovoid, a thin, continuous plagioclase mantle, and orientation of quartz and feldspar granophyres surrounding the ovoid.

mantled by higher-intensity blue-CL quartz, directly corresponding with Ti substitution for Si in the quartz: cores have 40-60 ppm Ti whereas rims contain 100-200 ppm Ti. The boundary between the core and rim is sharp (~5 μm). Like the ovoid feldspars, this texture results from decompression resorption and subsequent overgrowth at the emplacement depth. Additionally, the sharp (as opposed to diffuse) compositional boundary suggests that the Mount Scott Granite cooled quickly and largely remained thermally unperturbed.

In addition to the quartz and alkali feldspar, the granite contains a small amount (~6 vol.%) of ferroedenitic hornblende and Fe-rich biotite, typically interstitial to the preceding phases and as glomerocrysts with magnetite, ilmenite, titanite, fluorite, zircon, apatite, and allanite. Sub-solidus fluid interaction locally altered biotite to chlorite and magnetite to hematite.

Mafic enclaves, the second characteristic of the Mount Scott Granite, occur as two types at this location. Type I enclaves are dark and angular, microgranular, and largely composed of plagioclase and hornblende with lesser biotite and magnetite. Magnetite is commonly concentrated near margins or in zones where plagioclase is heavily altered. Type II enclaves are round blobs with relatively high, but variable color index. These are fine grained and composed of equal amounts of plagioclase, alkali feldspar, and subhedral hornblende, with lesser quartz, magnetite, and titanite.

This locale also contains quartz veins and features rarely found elsewhere in the Mount Scott Granite: microgranite pods and pegmatitic pods (Figure 3) and dikes with miarolitic cavities (vugs). Quartz veins here are typical of those found in the Wichita Mountains – thin linear features composed entirely of quartz. Veins here typically trend north – south and cross-cut the other features such as the microgranite pods. Although Mount Scott Granite may be fine grained or contain rare aplite/pegmatite dikes elsewhere, pods of microgranite are unique to this locale. They vary in size but are typically 25 to 50 cm in diameter; larger examples (as much as 2.5 m) are found to the west of the quarry pit. The pods are roughly oval in shape, although some have irregular upper boundaries. Boundaries are always sharp, and the microgranite contains weakly granophyric alkali feldspar and quartz as well as hornblende, hematite, zircon, and apatite. The pods contain ovoid feldspars but in lower concentrations than seen in most of the granite. Also atypical of the Mount Scott Granite are pegmatite pods and the thin short pegmatitic dikes found here, generally containing alkali feldspar and quartz. Some pegmatite pods include cavities or vugs, most of which contain mafic clays and calcite.

Figure 3. Photograph of a pegmatite pod, on the west end of the quarry. A U.S. quarter is shown for scale. The pod is dominated by large quartz and pink alkali feldspars. Mafic minerals are largely altered to clays. The pod contains prominent vugs, some of which are filled by secondary calcite and clays.

Diabase Dikes

Two spectacular examples of thin Diabase dikes occupy the west end of the quarry. The dikes are fine grained and not noticeably porphyritic. They are largely dominated by subhedral to anhedral plagioclase laths, magnetite and ilmenite and rare hypersthene crystals, surrounded by augite. Dikes such as these are found cutting most of the pre-Reagan units within southern Oklahoma (Gilbert and Hughes, 1986), and their emplacement likely continued to the last stages of aulacogen magmatism (Myers et al., 1981). Although common in the Wichita Mountains, their relatively fast weathering rate reduces most surface exposures to saprolite-filled trenches that typically obscure the dikes (see Stop 7).

Here, quarrying provides excellent exposure of two dikes cross-cutting the granite (Figures 1 and 4). While these dikes are also exposed in the quarry wall, thin dark layers of manganese oxides cover and partially obscure much of the exposure, particularly the east dike. The best view of the dikes is on the quarry floor. The west dike is 0.12 m wide, strikes 350°, dips 82° E, and continues to the top of the wall where it is weathered away from the hill profile, producing a notch. The east dike is located 4.19 m from the west dike, strikes parallel to it, but dips 86° E. Most interestingly, the east dike is split into two near-parallel lobes separated by a septum of granite.

Both dikes, including the two lobes of the larger east dike, terminate just below the quarry floor along the edge of lake. For the bifurcated east dike, each lobe clearly exposes lower terminations and does not continue on downward "out of sight." The west lobe's local floor (lowermost extent) is exposed adjacent to the lake (Circle 1, Figure 4). The floor of the east lobe is 1.3 m above this, about 0.5 m from the west lobe (Circle 2, Figure 4).

The diabase preserves chilled margins on the exterior walls of both lobes of the east dike (Figure 5) and partially on the interior wall of the west lobe. Within these chilled margins, plagioclase lath size decreases from 1 to 2 mm to 0.05 and 0.25 mm (weakly porphyritic, <5 vol.%). These plagioclase laths are not noticeably aligned within the dike interior and only weakly aligned within the chilled margins.

The texture of much of the granite septum between the two lobes is fine grained with fewer ovoid phenocrysts – vastly different from typical Mount Scott Granite (Circle 3, Figure 4). At the northernmost floor exposure, the septum adjacent to the lobes is much darker (Circle 4, Figure 4 and Figure 6). In other places, whole pieces of diabase are separated from the dike and form xenoliths surrounded by the

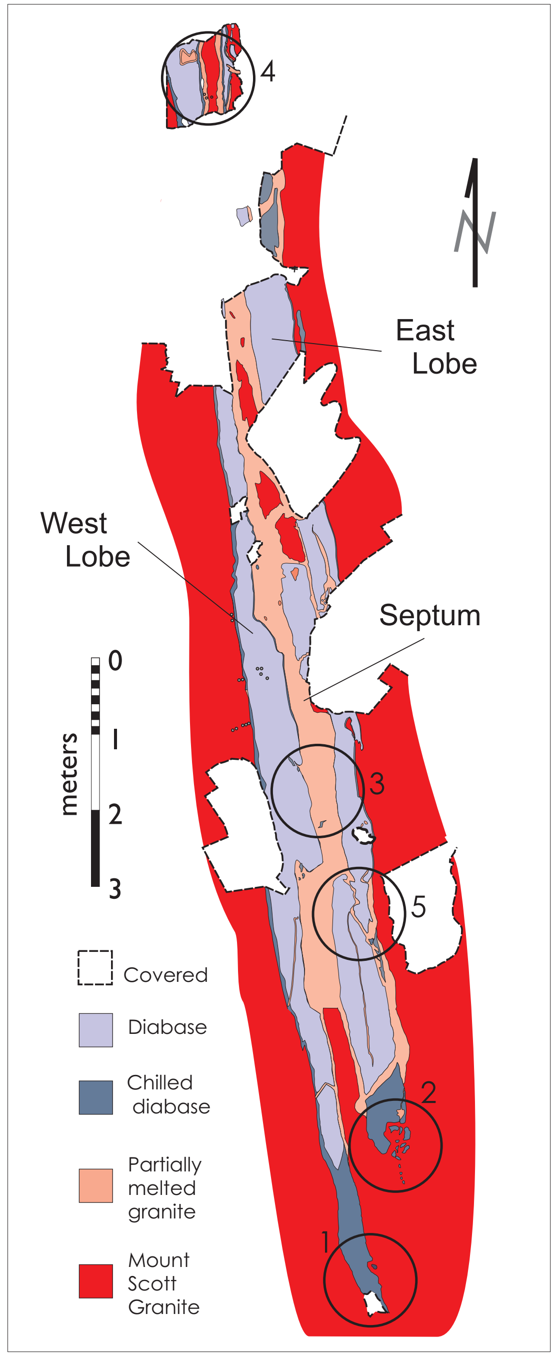

Figure 4. Geologic map of the larger eastern dike, floor of the main quarry, Lake Elmer Thomas Dam. Circles correspond to locations of features described in text. 1. Floor of west lobe. 2. Floor of east lobe. 3. Fine-grained granite derived by partially melting Mount Scott Granite. 4. Darker fine-grained granite, result of limited contamination of the granite septum (see Figure 6). 5. Intrusion of fine-grained granite into dike (see Figure 7). Modified from Price et al. (2012).

Figure 5. Plane-polarized-light photomicrograph of a standard thin section of a sample from the eastern exterior wall of the east dike. Note coarser, unoriented plagioclase laths in dike interior (left), mantled by finer laths at the contact with the granite. Sample shows chilled margin of diabase against granite, with limited recrystallization of the granite adjacent to the diabase. The remainder of the thin section is typical Mount Scott Granite.

septum granite. Locally, stringers of the same granite also cross-cut the diabase dike (Circle 5, Figure 4 and Figure 7) and fill in space between the dike and the exterior wall of the east lobe.

The exterior walls and floor of the east dike are demonstrably altered. Alteration includes increased perthite exsolution, sericite growth, and hematite staining in feldspars, as well as substantial modification of amphibole and biotite grains immediately adjacent to the contact. The altered contacts exhibit a less intense orange color compared to the surrounding granite. Alteration does not penetrate deeply, and its influence is limited to within less than a millimeter of the dike contact in places (Figure 5). Beyond the altered zone, the granite is typical and seemingly unperturbed Mount Scott Granite, marked by perthitic ovoids, granophyre, and titanium zoning in quartz.

DIKE-GRANITE RELATIONSHIPS

Dike Emplacement

The dikes' vertical termination and a lack of aligned grains suggest these dikes did not serve as long-lived conduits for magmatic flow. They were instead horizontally propagated fractures filled with poorly-crystalline magma that cooled in place. Horizontal propagation of dikes (sub-vertical sheets of magma) results when the sum of the forces driving the magma upwards is nearly balanced by the sum of the forces resisting ascent. Magmastatic analysis for a basaltic magma sourced at a mid-crustal mafic complex and ascending through SOA crust at its tensile strength produces a positive head for depths greater than 0.2 km (Hogan et al., 1998). Above 0.2 km, the driving pressure remains below the lithostatic pressure, preventing further ascent or uplift of the overlying strata. This indicates that the Diabase magma remained subvolcanic and did not reach the surface, intruding as vertical sheets (i.e., dikes) but not as horizontal sheets (i.e., sills).

Intrusive Timing

Like other exposures of the Diabase in the Mount Scott Granite, it is clear that this basaltic magma post-dates the solidification of the intrusive suite. But this locale provides unique insight into the timing of the two events. The septum granite and stringers in the east dike could have only formed if dike intrusion closely followed granite solidification.

The septum granite is a product of dike-induced melting. The granite in the septum and connected stringers is similar to the Mount Scott Granite but contain few ovoid feldspars. The darker color and the presence of diabase xenoliths in this septum suggests limited mixing of diabase and granite melt. The granite stringers exhibit geometries consistent liquid-intruded tensional fractures within the dike.

Figure 6. The east dike as exposed adjacent to the quarry wall (circle 4, Fig. 4). The granite material in the septum between the two lobes is dark, possibly indicating that it formed from a felsic melt contaminated by a mafic one.

Across the SOA, partial melting from Diabase intrusions is anomalous, noted only in large dikes (e.g., width = 6.8 m (Denison, 1998)). Basaltic magma temperatures were likely near 1200 °C, a temperature that greatly exceeds the solidus of many host rocks (near 850 °C for the Mount Scott Granite (Price et al., 1999)). However, thin static dikes cannot transfer sufficient heat to raise the temperature of cold host-rock above its solidus. Only large dikes, or those that serve as conduits with sustained flow, induce partial melting of the wall rocks.

The dikes here at Lake Elmer Thomas do not seem to meet the requirements for inducing partial melting. They are thin. Their interior mineral fabrics are unaligned and their propagation direction is horizontal, consistent with one-pulse emplacement rather than prolonged flow. Correspondingly, the dike's exterior walls exhibit a recognizable chill zone, and the adjacent granite on the exterior walls is largely unmelted and minimally altered.

Whereas the exterior granite walls surrounding the east dike show little evidence of partial melting, the septum between the two lobes contains a large volume of partial-melt-derived granite. It is likely this represents a region of substantial melting due to increased heating, in contrast to the exterior walls. If we consider conduction to be the principle heat-transfer mechanism, the septum would receive heat from both lobes. Unlike the exterior walls which can move heat away in a dike-perpendicular direction, the heat in the septum is "trapped" and must largely diffuse out in a dike-parallel direction. The heat "buildup" in the septum might induce temperatures above those seen along the exterior walls.

The presence of melted granite prompted Price et al. (2012) to use a simple Stefan heating thermal model to examine heat distribution. The model employed a simplified cross-section of the east dike with the mathematical origin of the semi-infinite half-space at the midplane of the west lobe (Figure 8). The model is strictly illustrative; it is a one-dimensional numerical model that does not permit heat into or out of the cross-sectional plane. It neglects latent heat due to crystallization and volatilization. It assumes reasonable temperatures for the diabase liquid and for its solidification, and it utilizes generally accepted thermal-conductivity parameters for these rock types.

Figure 8 shows time profiles from a cooling model for diabase instantaneously emplaced at 1200 °C into 500 °C Mount Scott Granite. The first time step is 1.5 hours after the start time (Figure 8A), additional curves are plotted time intervals that each double the previous one (e.g., the next curve is 3 hours). The model requires a little under a day for the west lobe (Figure 8B.) and four days for the east lobe to solidify (Figure 8C), assuming the diabase is completely crystalline at 1050 °C (DS in Figure 8). Within eight days after intrusion of the dike, the entire septum region reaches a maximum temperature that is above the Mount Scott Granite solidus temperature (GS in Figure 8C.) while the temperature of the granite along the exterior margins remains below the solidus.

The model only reaches melting conditions in the septum. Based on the temperature profiles, melting began along the internal margin of the east lobe two days after intrusion and propagated inward. For a brief period, a small amount of diabase and granite would be molten, permitting the possibility of limited mixing or rapid diffusive interchange producing the darker granitic rock in the septum. Even after the dike lobes are solid, the model places the granite septum above its solidus for two weeks (likely to be longer given latent heat). Contractional fractures would form as a consequence of dike solidification and cooling. Partial melt from the septum would intrude the dike and form the small stringers like those in Figure 7. Finally, the model reaches reasonable solidification temperatures for the granite partial melt within two months (Figure 8D).

Although the model is illustrative, the results provide significant insight into the dike's timing. The model indicates that the dike intruded warm granite. The dike is still too small to provide sufficient heat to melt the septum of Mount Scott Granite at ambient (geothermal) temperatures, estimated to be near 100 °C. The temperature of the Mount Scott Granite must have been significantly higher than ambient, i.e., it was still cooling following intrusion. This implies that radiometric dates of these Diabase dikes could overlap those of the Mount Scott Granite.

CONCLUSION

This stop contains an excellent, easily accessed exposure of Mount Scott Granite and Diabase. The quarry's setting at a typical eastern Wichita Mountains rocky knob reveals common structures and weathering features in the granite. Easy access and fresh exposure of both granite and diabase permits viewing of unweathered rock, a rarity for both units. The granite exhibits several features here considered to be uncharacteristic of the granite as a whole. The fortunate intersection of extensive quarrying and dike geometries provides unique insight into the intrusive relationships of these two magmatic bodies. The presence of dike floors suggests that the diabase locally reached terminal ascent subvolcanically. Measurements and observations,

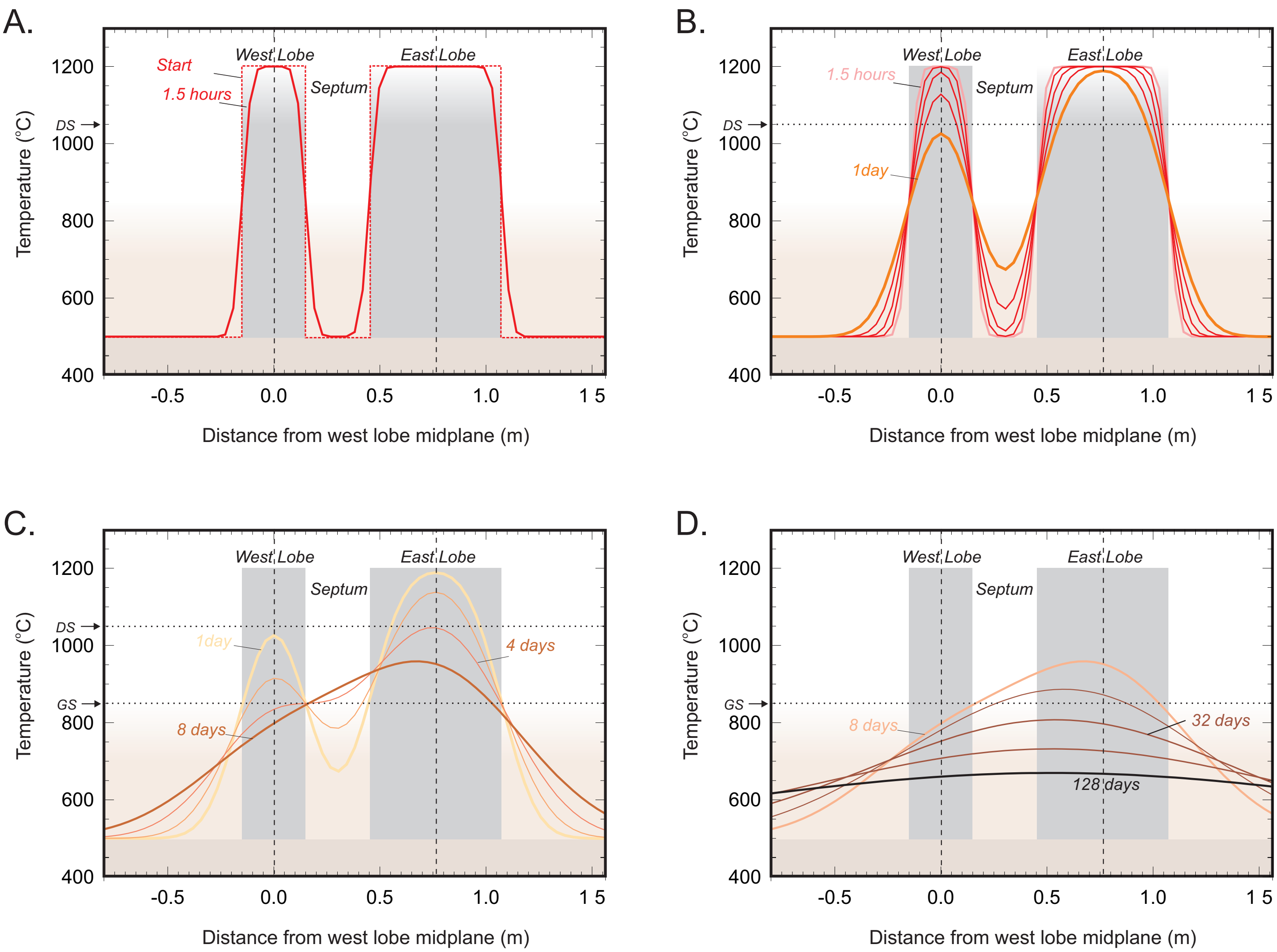

Figure 8. Time slices for a Stefan cooling model for instantaneous intrusion of both east dike lobes at 1200 °C into Mount Scott Granite at 500 °C. A. Start (t_0) to 1.5 hours. Red dotted line is the initial thermal profile, thick red line is profile after 1.5 hours. Lines in subsequent panels each reflect a doubling of the elapsed time. B. 1.5 to 24 hours. East lobe reaches DS, a likely temperature for diabase solidification. The model shows the west lobe is completely solidified in one day. C. 1 to 8 days. East lobe solidifies and septum exceeds GS, an experimentally-determined temperature for the Mount Scott Granite's solidus. Modeling suggests that dike intrusion and cooling would adequately heat the entire septum past the solidus, permitting significant partial melting. A small amount of partial melting would ensue prior to solidification of the lobes, providing an opportunity for chemical exchange between diabase and granite liquids. The bulk of the heat arrives following diabase solidification, permitting intrusion of granitic melt into fractures in the dike. D. 8-128 days. Septum solidifies and begins to cool.

coupled with simple thermal modeling, further indicate the contemporaneous nature of some of the mafic and felsic magmatism within the SOA.

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Stop 6. The summit of Mount Scott

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Location: At end of road to summit north off of OK Hwy 49 ~1.8 mi west of Wichita Mountains National Wildlife Refuge boundary, 8.9 mi west of exit 45 off of Interstate 44, and 2.7 mi east of intersection of Hwy 49 and OK Hwy 115, Comanche County, Oklahoma. C N½ SE¼ sec. 11, T. 3 N., R. 13 W., Mt. Scott 7.5' quadrangle. UTM coordinates: 542880E, 3844610N.

INTRODUCTION

Mount Scott's massive form and prominence as the easternmost high peak makes it an icon of the Wichita Mountains (Fig. 1). Its broad slopes have always permitted a relatively easy climb to an unparalleled vista; the paved roadway further eases the ascent. The summit's view, long valued by inhabitants as a lookout and treasured by tourists for its inspiration, also offers geologists a view into the region's past. The top of the mountain provides displays of the regional nature and local details of the Southern Oklahoma Aulacogen and subsequent geological processes.

Mount Scott exhibits the greatest amount of vertical relief in the Wichita Mountains, rising from the surface of Lake Lawtonka at 1348 feet [411m] to the parking lot at 2464 feet [751m] a.s.l. It is not the tallest landform in the region, a distinction that goes to unofficially named Haley Peak (34°50'22.46"N, 98°48'8.06"W, 2,481 feet [756 m] a.s.l.). One other peak, Mount Pinchot (34°47'58.23"N, 98°46'21.25"W), rises to similar elevation of 2,477 feet [755 m]. Both Mount Pinchot and Haley Peak are located on the western edge of the eastern Wichita Mountains, 22.5 and 27 km away, respectively. Like Mount Scott, both are underlain by Mount Scott Granite, which is continuously exposed over that distance. In addition to these landmarks, numerous peaks and promontories in the eastern Wichita Mountains share common summit elevations; there are several at about 2,200 feet [670 m] and others at 2,150 feet [655 m]. Many of these landforms exhibit flat summits, and may represent a common erosion surface or surfaces related to the Southern High Plains pediment (Harrell, 1993; Jerris and Hogan, 2008).

The 3-mi (5-km) spiral drive to the Mount Scott summit parking area rises through the thickest continuous section of the Mount Scott Granite. It reveals several noteworthy features. At the start of the ascent, the road passes the south end of a boulder field, a valley filled with poorly sorted, but large (3-m) boulders of Mount Scott Granite (Fig. 2). This location is the best exposure of the Mount Scott Granite boulder fields, many of which are located in south-flowing drainage valleys and on high slopes in the region between Mount Scott and Quetone Point (1.65 km to the west). The road ascends past exposures of weathered and cut granite, and provides numerous views of the surrounding area. Two miles (3.2 km) from the start, the road steps through excellent exposures of exfoliation fractures and surfaces (Fig. 3).

The road ends at the summit loop and parking lot, an expansive area that reflects the relative flatness of the mountain's top. The summit provides exposures that illuminate the nature of the Mount Scott Granite, including its weathering attributes, its intrusive history, and its place in the regional geologic processes. Full exploration of the rocks and vistas requires a traverse around the outside of the loop.

SUMMIT EXPOSURES

The surface of the summit is marked by large boulders of granite and thin soils that support grasses and a sparse population of juniper and a few oak trees. Numerous in-place boulders are found along the rim and region south of the parking lot. These monoliths and outcrops exhibit weathering features that contrast with cut exposures like those seen at Lake Elmer Thomas Dam (Stop 5).

The Mount Scott Granite weathers from pink-red to brick- or orange-red. The ovoid alkali feldspar phenocrysts that are gray in fresh sections are typically lighter colored or plucked out, leaving oval pock marks. Dark staining by manganese minerals is common, as it is on recent exposures (e.g., at Stop 5). The weathered granite is also marked by

Figure 1. Mount Scott's eastern face as viewed from Lake Lawtonka at its dam at Medicine Park. The landform is the easternmost high peak in the Wichita Mountains.

light green and green-yellow splotches of lichens. Exfoliation fractures and intersecting, near-vertical joints penetrate the granite to significant depths (Price et al., 1998), providing conduits for water-rock interaction. Fluids introduced through these fractures produced martite (magnetite altered to hematite) and clay minerals (altered biotite and amphibole). In the distant past, extensive weathering disaggregated the rock along joint surfaces, promoting the development of corestones and then boulders (see description of tor topography and boulder formation for Stop 8 at Burford Lake).

VIEWS FROM THE SUMMIT LOOP

The vistas from the summit permit exploration of key geologic features of the Cambrian Mount Scott Intrusive Suite, the aulacogen, Pennsylvanian uplift, and Permian and recent erosion. As described by Price (this guidebook), the granite at this type locality is one of four granite bodies that are compositionally, temporally, and spatially related. All combine to form the Mount Scott Intrusive Suite, a tabular body that currently presents 55 km x 17 km x 0.5 km of exposure, the bulk of which is Mount Scott Granite. The four granite bodies - the Medicine Park, the Rush Lake, the Mount Scott, and the Saddle Mountain Granites - originate from a common source that ponded 7 to 8 km in the aulacogen crust. These ascended to a common emplacement horizon of < 2 km depth, each intruding a weakness formed by the unconformity between earlier mafic intrusions and the overlying volcanic pile (Hogan and Gilbert, 1997; Hogan et al., 1998). The Mount Scott Intrusive Suite is among the earliest of the exposed granite intrusions; it was locally followed by the Quanah Granite that was emplaced into the same horizon. Partial local unroofing and extension rapidly followed, evidenced by the subvolcanic basaltic (diabase) (Price et al., 2012) and felsic dikes that cut the granite. Magmatic quiescence was followed by regional subsidence, resulting in the formation of a deep basin active from the Late Cambrian through the Early Devonian. Basin deposits covered aulacogen rhyolites with sands followed by thick carbonates (Miall and Blakey, 2008). Pennsylvanian compression of this region (part of the Ancestral Rockies orogeny) resulted in extensive folding and faulting of the basin fill, overall uplift of the aulacogen products here, and downwarping to the north in the deep Anadarko Basin (Soreghan et al., 2012). Erosion into the uplifted blocks uncovered the aulacogen materials and continued into the Permian. Permian rocks and exposures were partially buried by their own detritus (Al-Shaieb et al., 1980; Gilbert, 1982). East-to-west fluvial systems also buried the mountains and hills at this time. These fluvial stata have been recently removed to reveal the Permian landforms, modified by recent erosion (Gilbert, 1982).

The modern environment and its impact on soils, rocks, and landforms greatly aids viewing the lithologies at a distance. Hills underlain by rhyolite are broad, smoothly rounded, and treeless but grass covered. Those underlain by granite are rugged and rocky, with thin soils that deepen in the larger fractures (linears) that cross-cut the exposures. The mafic bodies exhibit greater weathering and are confined to valleys and slopes under granite mantles; their thicker soils promoting robust habitats for post oak trees. The early Paleozoic sedimentary rocks, dominated by carbonates, are relatively free of tree cover. Wind-power turbines mark the crest of the hills underlain by the carbonates. Permian sediments mantle low-lying, flat grasslands.

Figure 2. A view north on the lowest southwestern slope of Mount Scott near the base of the mountain on the spiral scenic drive that ascends to the summit. Large boulders of Mount Scott Granite fill in this valley.

A full circle view from the summit encompasses the Meers Valley, Lakes Lawtonka and Elmer Thomas, the village of Medicine Park, the rhyolite hills that underlie much of Fort Sill's firing range, the intermountain plateau known as Jed Flat, the granite peaks made of Mount Scott and Quanah Granites, the contact with the underlying mafic intrusive units, and the deformed Cambro-Ordovician rocks of the Slick Hills.

TO THE EAST

The eastern view is of the southwestern end of the Meers Valley, which opens to the rolling plains typical of the region (Fig. 4). The valley floor in this view is underlain by Permian Hennessy Formation, fluvially deposited red-brown shale with variegated siltstone and tan sandstone (Stanley et al., 2005). The rocky hills on the south side of the valley are composed of granite that is part of the Mount Scott Intrusive Suite. The nearest is the Medicine Park Granite, which shares contacts with the Rush Lake Granite and the easternmost outcrops of the Mount Scott Granite. The Medicine Park and Rush Lake Granites have relatively small areal distributions compared to the Mount Scott Granite. Each granite exhibits distinctive chemical compositions and mineral textures. Contact relationships suggest that all are roughly contemporaneous, but the Medicine Park Granite is older than the Rush Lake Granite, which is in turn older than the Mount Scott Granite (see Price, this guidebook, for further details).

In the foreground, to the east and southeast is Lake Lawtonka, an impoundment of Medicine Creek and the reservoir for the City of Lawton. Medicine Creek is the principle drainage for the Meers Valley, but here it cuts south through the Medicine Park Granite exiting to Cache Creek through the lowlands. From the lake, it cuts into re-

Figure 3. Excellent exposures of curved exfoliation fractures as seen along the scenic drive roughly two miles from its start. These are similar to features seen at Stop 5 and elsewhere. The fractures are permeable conduits for runoff and seepage (note ice and water staining on surface, left side of image).

Figure 4. The view to the east and southeast includes Lake Lawtonka, an impoundment of Medicine Creek as it crosses the southern edge of the Meers Valley on the western side of the village of Medicine Park. The rocky hills of Medicine Park are underlain by three of the four granite bodies that comprise the Mount Scott Intrusive Suite (see Price, this guidebook), the Mount Scott, Rush Lake, and Medicine Park Granites. The smooth, rounded hills and

sistant granite and rhyolite hills, indicating that Medicine Creek's geometry was likely affected by the now-removed Permian overburden. Slopes formed on the covering strata forced the channel to incise the fossil topography (Gilbert and Powell, 1988); this is evident at Medicine Bluffs further downstream (obscured from view). A similar feature is seen on the cliff along the southern shore of Lake Elmer Thomas, on Pratt Hill. Here, a rounded hill of Carlton Rhyolite, most likely a Permian landform, is incised by recent erosion from now impounded little Medicine Creek (see "Cliff" on Figure 4).

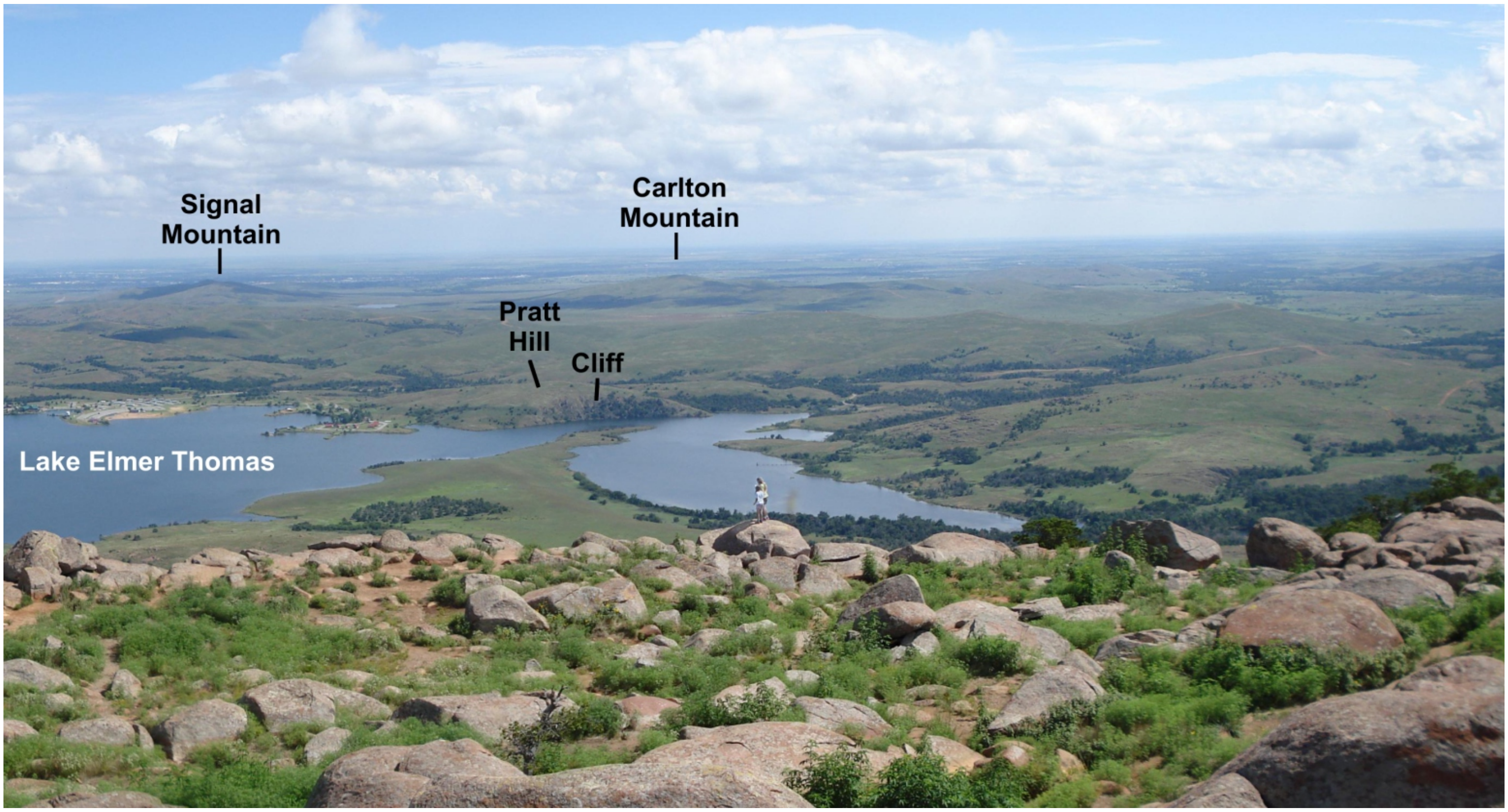
TO THE SOUTH

A raised observation platform marks the south end of the parking lot and provides and eyrie-like view of the southern vista. Lake Elmer Thomas, seen in the foreground (Fig. 4), is the impoundment of Little Medicine Creek, a small tributary of its aforementioned namesake, that runs from Jed Flat and the Holy City past the south side of Mount Scott and through the hills visited in Stop 4. Behind the lake, the low, smooth-surfaced, rolling and treeless hills are all underlain by the Carlton Rhyolite, including Carlton Mountain (1767 ft [539 m]) and Signal Mountain (1748 ft [534 m]). The rhyolite here is similar to that seen in the northern Wichita Mountains (Stop 4) excepting that quartz phenocrysts are found in some of the flow units in the Fort Sill section.

In the far west-southwest are lumpy-textured, rocky mountains (Fig. 5), such as Mount Lincoln (2,200+ ft [670+ m]) and Elk Mountain (2,280+ ft [695+ m]). These are underlain by the coarser-grained Quanah Granite. Elk Mountain has some of the largest corestones in the Wichita Mountains, as large as 30 to 65 ft [10 to 20 m] in diameter on its south and west flanks (Gilbert and Powell, 1988).

TO THE WEST

The view to the west looks out along the backbone of the eastern Wichita Mountains (Fig. 5). The higher eleva-



peaks to the south such as Carlton Mountain and Signal Mountain, are underlain by Carlton Rhyolite. Lake Elmer Thomas, in the foreground to the south, is an impoundment of Little Medicine Creek. Both it and Medicine Creek are superimposed on Permian topography, evidenced by recent cuts into the otherwise smoother landforms, like the cliff marked on Pratt Hill.

tions in the field of view are underlain by the Mount Scott Granite. The inclined mesa-like form of Mount Sheridan (2,450 ft [747 m]) is capped by the Mount Scott Granite and underlain by the Mount Sheridan Gabbro at its base. The granite-gabbro contact is delineated by the tree line, with the heavily forested slopes underlain by gabbro. This contact continues eastward and westward at roughly similar elevation. The contact is found along the north slope of Mount Scott, as seen in Figure 1.

The Mount Sheridan Gabbro is one of five distinct gabbro bodies within the Roosevelt Gabbros (see table 1, Stop 5). While the contact with the overlying granite seems sharp, close inspection reveals it to be somewhat ambiguous with regards to exposing a clear intrusive relationship. Interpretation is considerably hampered by a well-developed granite talus that covers much of the contact. To the west and southwest (to be seen at Stop 8), the granite and the gabbro both clearly intrude the much older Glen Mountains Layered Complex (GMLC) at the same horizon. The GMLC's antiquity is demonstrated partly by radiometric isotopes (Lambert et al., 1988) and more generally by its comparable nature to other deep-seated layered mafic complexes (Powell and Phelps, 1977). It is a mid-crustal magmatic body; its position under the shallowly emplaced granite results from significant unroofing prior to the felsic magmatism that formed the Carlton Rhyolite and the Wichita Granite Group (Gilbert and Powell, 1988). On this western part of the north slope, the Mount Scott Granite contains an igneous breccia of GMLC enclaves (Hames et al., 1998). This GMLC-Mount Scott Granite contact surface is regionally continuous into the Mount Sheridan Gabbro. Early studies logically concluded that both the GMLC and the Mount Sheridan Gabbro predate the granite, a view somewhat corroborated by early radioisotopic dates (Powell et al., 1980).

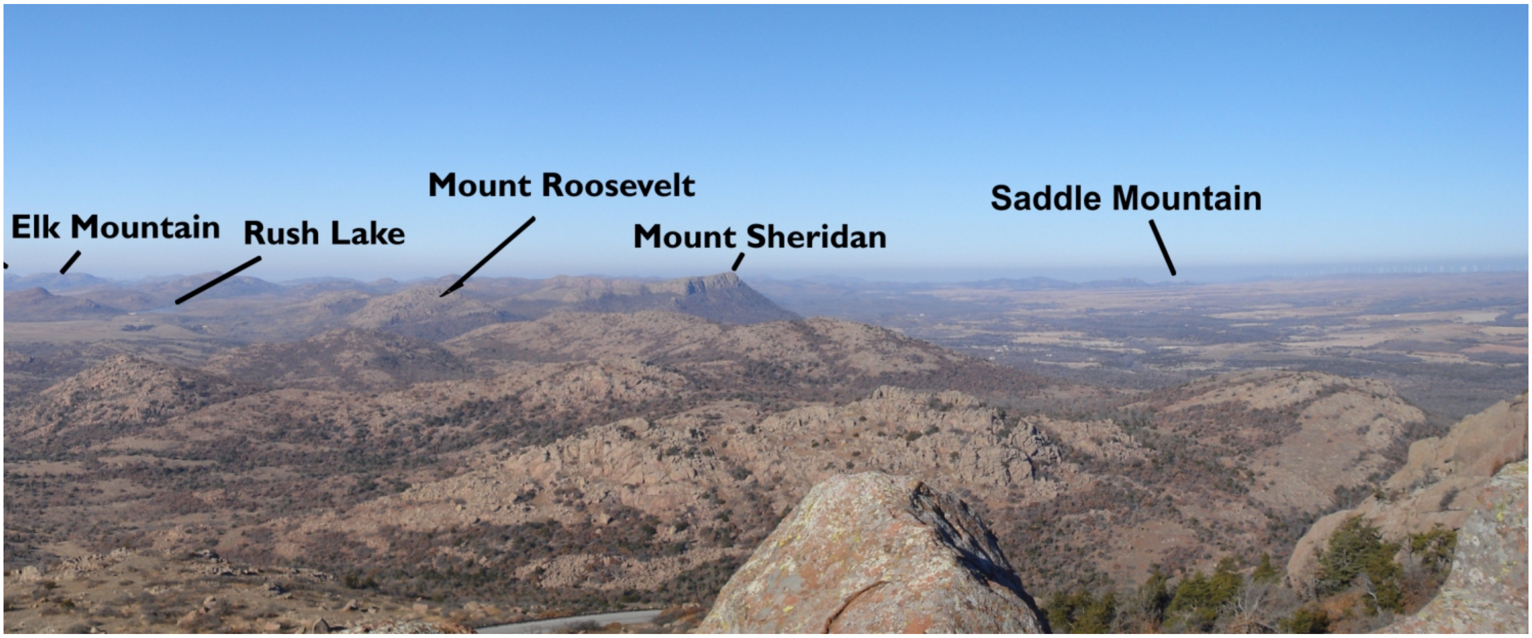
Prior workers concluded that the Roosevelt Gabbros were emplaced long after the GMLC but well before the Wichita Granite Group. But penecontemporaneous timing is supported by the detailed work of Hogan and coworkers on this and other contacts between the Mount Scott Granite

Figure 5. The view to the west from the summit of Mount Scott looks out on the interior of the high peaks region of the eastern Wichita Mountains. Most of the higher landforms are underlain by the Mount Scott Granite, extending north in the field of view to the region around Saddle Mountain. This northernmost region includes the Saddle Mountain Granite, the fourth unit in the Mount Scott Intrusive Suite. The tree line exposed along the eastern slope of Mount Sheridan roughly marks the contact between the granite and the underlying Mount Sheridan Gabbro, one

and the Roosevelt Gabbros, which are substantially different from the GMLC-Mount Scott contact described in the preceding paragraph. Amphibole-rich hybridized rock is found at the contact, containing a diverse set of enclaves partially encapsulated by the granite (Hames et al., 1998). Below the contact, the gabbro shows evidence of upward differentiation in the forms of increasing silicic composition and pegmatite pods and dikes (Lasco, 2011), suggesting that the Mount Sheridan Gabbro is a complete pluton (i.e., the granite did not intrusively split the pluton). The subsurface structure of other Roosevelt Gabbro intrusions (Price et al., 1998) and the general nature of pluton emplacement (Hogan et al., 1998) are also consistent with a relatively young age for the biotite-bearing gabbro. The relatively younger nature of the gabbro is supported by high-precision dating of the granite and gabbro (Hames et al., 1998; Wright et al., 1996).

Also to the west is a broad flat area bordered by Mount Scott Granite highlands to the north and south. This area, known as Jed Flat (Fig. 5), is largely covered with the Permian Post Oak Formation, locally a matrix-supported granite and rhyolite boulder-clast conglomerate. Beneath this is the Davidson Metarhyolite (Stop 6), which may be a hornfels representing high-temperature metamorphism of the lower part of the Carlton Rhyolite. The Davidson Metarhyolite may have locally served as the floor for the Mount Scott Intrusive Suite. On the northern and southern edges of the flat, the Davidson Metarhyolite and the Rush Lake Granite are juxtaposed along a roughly east-west contact. Both units terminate just east of the dam at Rush Lake. The northern edge of the Rush Lake Granite exhibits a roughly parallel contact with the Mount Scott Granite, the rock that underlies all of the peaks.

To the northwest, far in the distance, a few stray peaks protrude northward (Fig. 5). This region contains the fourth and youngest unit of the Mount Scott Intrusive Suite, the Saddle Mountain Granite. Whereas the Medicine Park and Rush Lake Granites are found near Mount Scott, near its lowermost contacts, the Saddle Mountain Granite is 20 km away, surrounded by some of the northernmost exposures of Mount Scott Granite. The granite grades from the granophyric texture typical of Mount Scott Intrusive Suite granites into a spherulitic texture typical of hypabyssal to extrusive felsic materials (Gilbert, 1986). Its textures, coupled with its compositional similarity to the Mount Scott Granite, suggest this unit developed near the top of the Intrusive Suite (see Gilbert (1986) and Price (this guidebook)).



of the five Roosevelt Gabbro plutons. The Roosevelt gabbros are the smaller, younger, and biotite-bearing bodies in the Raggedy Mountains Gabbro Group. South of this, Jed Flat is a relatively low-lying region, partially mantled by Permian sediments (the Post Oak Conglomerate) and underlain by Davidson Metarhyolite and Rush Lake Granite. To the far west, Mount Lincoln and Elk Mountain are two flat-topped mountains in a region underlain by the Quanah Granite, a distinctively different and younger granite compared to those of the Mount Scott Intrusive Suite.

TO THE NORTH

A small parking lot is found at the termination of the one-way loop at the north end of the summit. From here, one sees the wind turbines on the Slick Hills (2,000-2,100 ft [610-640 m]). Rhyolite forms the base of the hills to the east side of Blue Creek Canyon (Stumbling Bear Pass on Oklahoma Hwy 58 - Stop 4); lower Paleozoic sedimentary rocks (carbonates with minor clastics) are found elsewhere. A fault runs roughly parallel to the canyon, juxtaposing the upthrown Carlton Rhyolite against deformed Ordovician McKenzie Hill and Cool Creek Formations. East of the fault, the rhyolite is uncomformably overlain by the Cambrian Reagan Sandstone and Fort Sill Formations, continuing upsection through the Cambro-Ordovician Signal Mountain and the Ordovician McKenzie Hill and Cool Creek Formations (Donovan et al., 1988).

The sedimentary rocks and rhyolite of the Slick Hills represent the lithologies that once covered Mount Scott, but were eroded away during late Paleozoic uplift. Close to the north side of the valley and running parallel with the hill slope 3 mi (5 km) to the north of Mount Scott, the Meers Fault separates the Slick Hills from the relatively upthrown granite and rhyolite peaks, including Mount Scott. Because of this offset, the fault is associated with late Paleozoic movement. Slickensides, drainage offsets, and other attributes indicate the fault also moved in the last 1,200 to1,300 years with significant (3m) reverse throw and equivalent or greater left-lateral movement (Crone and Luza, 1990). Given the intensity of this recent activity, the fault represents significant regional earthquake risk.

The Meers Fault and the Blue Creek Canyon Fault crop out in the Slick Hills. Beyond the Slick Hills is the Mountain View Fault, buried under the Permian cover. It separates the upwarped Wichita Mountains (including the Slick Hills) from the downwarped Anadarko Basin where basement rocks are buried beneath 7.5 miles [12 km] of sedimentary rocks.

The surface of the Southern Oklahoma Aulacogen, after significant erosion, was buried by an estimated 15,000 ft (4.6 km) of sediment from Upper Cambrian through Mississippian time. The Slick Hills represent the lower 10,000 ft (3 km) or so of this sequence, and an addition thin section of these sediments underlies the southernmost mountains on Fort Sill (McKenzie Hill). More complete sections, particularly of the middle and upper 15,000 ft (4.6 km) are prominent in the Arbuckle Mountains about 60 mi (100 km) southeast.

EPILOG

The summit of Mount Scott permits regional examination of the magmatic products of the Southern Oklahoma Aulacogen and facilitates discussion of some of the details of the Mount Scott Intrusive Suite, the Roosevelt Gabbro and Glen Mountains Layered Complex, the late Paleozoic uplift and erosion event, and the modification by the modern environment. The mountain has long been revered as the sentinel of the plains. In light of ongoing research on the geology of the aulacogen and subsequent events, it continues to serve as an observation post to survey the Phanerozoic of southern Oklahoma.

ACKNOWLEDGMENTS

The author was first introduced to and impressed by Mount Scott on a structural geology field trip led by Dr. William G. Brown of Baylor University many, many years ago. The author's knowledge of the summit's compelling story is a direct result of discussions with Dr. M. Charles Gilbert of the University of Oklahoma. It was further shaped by lively discussions with Dr. John P. Hogan of the Missouri University of Science and Technology. The summit of Mount Scott served as a site of a number of these formative dialogs. The author is also indebted to Dr. Neil Suneson for his editing and organization of this field volume.

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Stop 7. Quetone Overlook, eastern Wichita Mountains

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Location: On north side of OK Hwy 49 ~1.7 mi west of intersection of Hwy 49 and road to top of Mount Scott (Stop 6, this guidebook) and ~1 mi east of intersection of Hwy 49 and OK Hwy 115, Comanche County, Oklahoma. SW¼ SE¼ NE¼ sec. 16, T. 3 N., R. 13 W., Mt. Scott 7.5' quadrangle. UTM coordinates: 539720E, 3843260N.

INTRODUCTION

From the east entrance of the Wichita Mountains Wildlife Refuge, the westward traverse of Oklahoma Highway 49 follows the eastern lowlands between the high peaks of Mount Scott Granite to the north and the hills of Carlton Rhyolite giving way to Mount Scott Granite to the south. The road roughly follows Little Medicine Creek valley into its uppermost reaches known as Jed Flat, a broad, gently sloping hill that divides the eastward-flowing branches of Little Medicine Creek drainage from the southward-flowing Blue Beaver Creek system. Approaching the stop, the road ascends roughly 100 ft (30 m) to Jed Flat, passing a road cut and small defunct quarry that is quickly followed by a right turn entrance to a short drive. The drive terminates at a parking lot known as the Quetone Overlook, so named for the nearby peak, Quetone Point (Figure 1), a granite knob with an elevation just under 2000 ft (610 m). The parking lot offers a view of the west face of Mount Scott (Stop 6) as well as the other easternmost high peaks. The flat is also frequented by the refuge hoofstock - buffalo, longhorn, and elk - making it an excellent place to view wildlife. In terms of geology, the Quetone Overlook holds subtle but important clues to the intrusion of the Mount Scott intrusive suite and the nature of Permian sedimentation.

A complete exploration of the Quetone Overlook geology is somewhat time-consuming, and the geologic story covers three areas: the flat adjacent to the parking lot, the quarry and highway cut, and the canyon across the highway. Aside from quarry exposure and road modification, exposures are products of the Little Medicine Creek system. The creek forks upstream of Lake Elmer Thomas, and two prominent channels dominate this stop. This stop description informally refers to the meandering channel on the flat as upper Little Medicine Creek and the canyon as lower Little Medicine Creek.

GEOLOGIC UNITS

Quetone Overlook is a valuable stop because it reveals the interrelationships among several key units associated with aulacogen felsic magmatism. A clear view of these is somewhat impaired by the highly weathered, highly fractured, and poorly exposed nature of these rocks. They are a challenge to decipher, but uniquely illuminate the intrusion of the Mount Scott intrusive suite and its affect on the older rhyolite. The stop's best feature, however, is the exposed quarry that produces a rare section through typical Permian cover in the granitic Wichita Mountains.

AULACOGEN UNITS

Carlton Rhyolite

The exposures of the Carlton Rhyolite here pale in comparison to others in the region, some of which are more thoroughly and eloquently described in this guidebook by Hanson and coworkers (see Finegan and Hanson, this field guide). At Quetone Overlook, exposures of the rhyolite are limited to the stream cut of lower Little Medicine Creek on the south side of Highway 49 (Figure 2). The rhyolite is porphyritic Carlton Rhyolite and is similar to that found on Fort Sill to the south and east. Like exposures in the Slick Hills (northern Wichita Mountains, Stop 4, this guidebook), the rock is brown weathering to orange and strikingly porphyritic, with phenocrysts of angular, orange-pink microperthite. But in contrast, the rhyolite at Fort Sill contains rounded, dark-gray quartz phenocrysts. These are set in a fine-grained matrix of largely feldspar and quartz with acicular needles of magnetite.

The rhyolite appears to have been partially recrystallized due to sub-solidus thermal alteration. This is evidenced by a coarser groundmass and a weak granoblastic texture. This alteration is observable only under a petro-

Figure 1. A panoramic photograph of the high peaks north of the parking lot at Quetone Overlook. The meandering upper Little Medicine Creek has produced a flat pavement that separates the parking lot from the foothills made of Mount Scott Granite. The flat contains exposures of Rush Lake Granite and Davidson Metarhyolite. Both units are extensively fractured and highly weathered. The high peaks of Mount Wall and Quetone Point separate the overlook from Meers Valley to the north.

graphic microscope; hand samples and exposures of the recrystallized Carlton Rhyolite are indistinguishable from the more typical unaltered volcanic rock.

This guidebook underscores the voluminous and widespread nature of the Carlton Rhyolite Group. The Fort Sill area contains an extensive exposure, stretching 18 km to the southeast. It underlies most of the hills in that direction. Exposures reveal a minimum thickness of 90 m (Hanson et al., 2012). These are the products of flowing lavas, as opposed to ignimbrites; individual flows are marked by flow breccias and flow folds near the top, chilled and pumiceous textures, flow lamination, and peperite at the base, and and a massive felsitic center with flow banding and column joints (Finegan and Hanson, this guidebook).

This rhyolite occurrence is near the western edge of mapped Carlton exposures in the southern Wichita Mountains. Quetone Overlook is roughly 2.2 km due north of Thompson Hill (1685 ft or 514 m), on the western end of one of the thicker sections of the rhyolite. It is found only in a few low-lying locations west of the slopes of Thompson Hill. The hills to the southwest are Mount Scott Granite.

Davidson Metarhyolite

The Davidson Metarhyolite is fine-grained (non-granitic) rock that is distinguishable from the Carlton Rhyolite in hand specimen. It is exposed at this stop as a pavement surface on the flat adjacent to the parking lot and the rise to the east of it and along the upper elevations of the lower Little Medicine Creek canyon south of the highway. While it may contain granoblastic (phenocryst-like) feldspar, much of it is aphyric with feldspar or quartz stringers, chlorite spherules, and glomerocrystic mafic minerals and accessories. It is further subdivided into a banded facies and a massive facies.

Metarhyolite is found in outcrops adjacent to three of the units of the Mount Scott Intrusive Suite: the Mount Scott Granite, Rush Lake Granite, and Saddle Mountain Granite (see Price, this guidebook). Its limited exposures suggest that it is volumetrically minor. Although metarhyolite float is seen on the northeast slope of Mount Scott, in-situ exposures are confined to the west-northwest – east-southeast-trending topographically low swath traversed by Highway 49. In the Hide-A-Way and Mount Scott Picnic areas, adjacent to Lake Elmer Thomas 3 km to the east, outcrops are predominantly the banded facies and are stratigraphically beneath a metasedimentary unit, the Pratt Hill Quartzite, which, in turn, is overlain by the rhyolite (Finegan and Hanson, this guidbook; Gilbert, 1982; Miller et al., 1982). Locally, exposures are dominated by the massive facies exposed at elevations above or equivalent to the Carlton Rhyolite. Much of the unit is buried beneath the Permian Post Oak Conglomerate, but its contacts with the Rush Lake Granite and the Mount Scott Granite are locally exposed. Additionally, meter-sized xenoliths of the metarhyolite are entrained in the Rush Lake Granite.

The banded facies of the Davidson is dominant in the Hide-A-Way area, but at Quetone Overlook it is confined to the southernmost exposure on Figure 2, south of lower

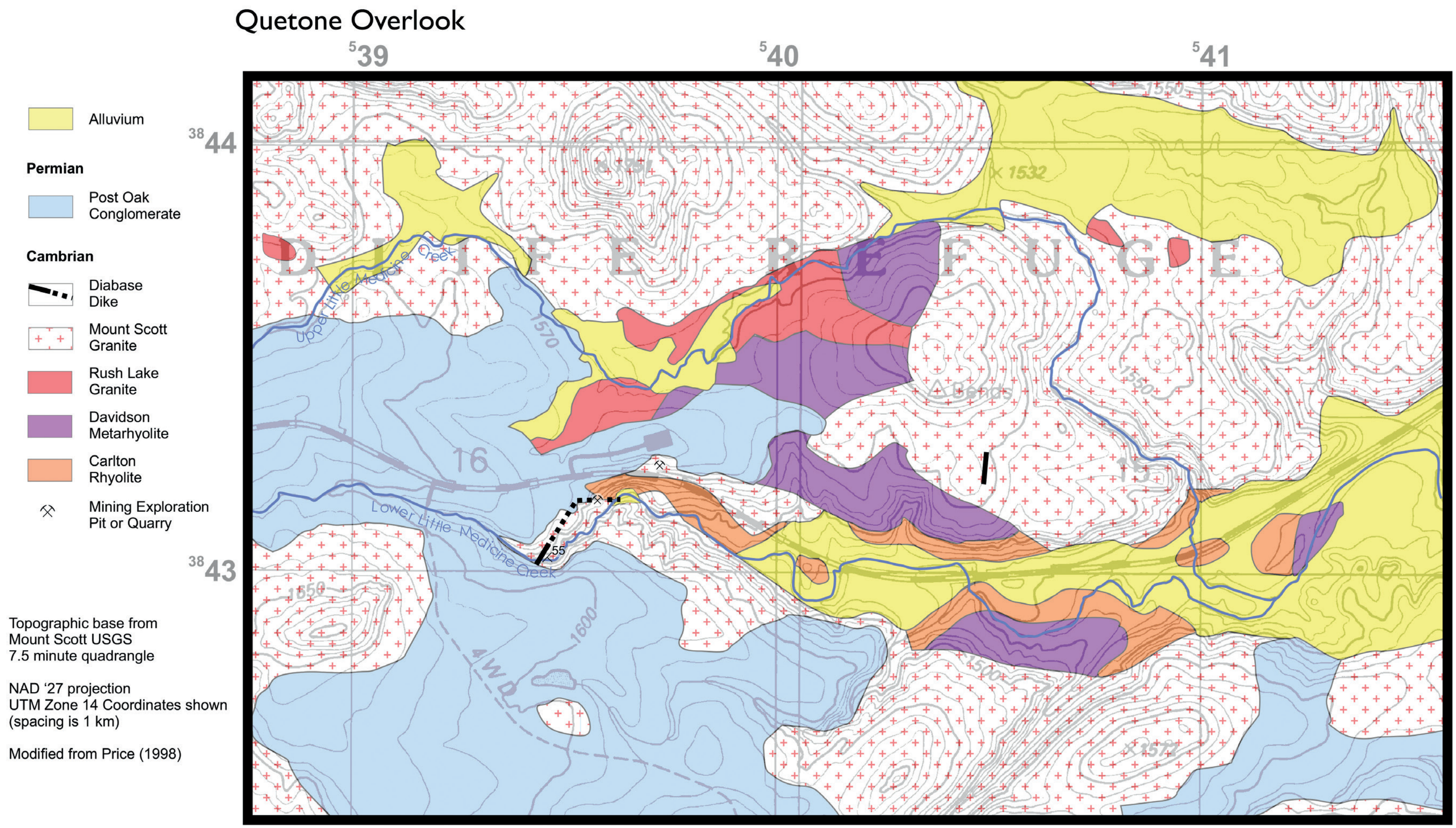

Figure 2. A detailed geologic map of the Quetone Overlook area. The map is based on Price (1998) and revised using newer satellite imagery that better outlines the alluvium and Permian Post Oak Conglomerate. Generally, the map shows Carlton Rhyolite in the valley of lower Little Medicine Creek, with adjacent Davidson Metarhyolite and Rush Lake Granite. Mount Scott Granite dominates the map. All units are covered by Permian sedimentary rock and recent alluvium and detritus.

Little Medicine Creek. It is recognized by its buff color and distinctive dark-gray bands contorted into isoclinal folds. The rock contains abundant fine-grained granoblastic quartz and alkali feldspar, and minor glomerocrysts of both. Matrix feldspars are smaller than and interstitial to quartz crystals. The feldspars are mostly altered to sericite. Hematite ± chlorite ± muscovite ± biotite ± zircon are seen in thin sections but are typically too fine-grained to see in hand specimen. The bands are denser concentrations of opaque minerals (oxides) and altered mafic minerals. The matrix of the rock appears recrystallized throughout.

The unbanded Davidson Metarhyolite is the facies that is best exposed in the Quetone Overlook area. It is consistently feldspathic, fine grained, and highly fractured. It is typically pink and weathers to buff. It is mostly aphyric and microgranoblastic. Porphyroblastic examples have pink alkali-feldspar glomerocrysts. Samples contain alkali feldspar and quartz with small and variable amounts of oxides, sericite, and chlorite. The matrix quartz and feldspar are roughly equigranular. Epidote spherules (2 to 3 mm diameter) are locally prominent. These are visible at hand-sample scale as scattered dark splotches. The rock is commonly cut by thin millimeter-size veins of pink feldspar or oxide. It is also densely cut by linear fractures that are enhanced by weathering and that cause the metarhyolite to break into small angular blocks.

Rush Lake Granite

The Rush Lake Granite is also found in the pavement surface north and east of the parking lot. It is bounded on to the northeast and south by Davidson Metarhyolite and the Mount Scott Granite to the northwest and to the east. Better-exposed, less-fractured, and larger outcrops are found east of Rush Lake (on the western edge of Jed Flat), where they show both diffusely graded and sharp, interdigitating contacts with the Mount Scott Granite. Additional exposures are seen in and around the village of Medicine Park, east of the Wichita Mountains Wildlife Refuge.

The Rush Lake Granite is red weathering to brick-red and orange. It is porphyritic with angular pink alkali feldspar phenocrysts surrounded by granophyre. Granophyre growth boundaries are well defined in coarser samples by distinctive "chains" of quartz crystals (typically < 1 mm wide and 2 to 3 cm long). The rock color index varies from 3 to 5 vol. % and consists of biotite, hornblende, and oxides. Mafic silicates have been extensively altered to chlorite and clay minerals. Accessory minerals include apatite, fluorite, zircon, and allanite. The rock contains abundant 2 to 50 mm diameter miarolitic cavities and microscopic to 3-cm-wide quartz veins.

Mount Scott Granite

The Mount Scott Granite dominates the geology of the Quetone Overlook (Figure 2) as it does the entire high peaks region of the eastern Wichita Mountains. It is exposed on both sides of lower Little Medicine Creek and underlies the foothills and high peaks to the north. With the exception of a few shallow mining pits, fresh examples of the granite are not seen at this stop; unweathered exposures are best observed at Stop 5.

The rock is a pink to brick-red alkali-feldspar granite with mafic enclaves and 2 to 3 mm gray ovoid phenocrysts of alkali feldspar set in a variably granophyric matrix with minor plagioclase, amphibole, biotite and accessory minerals. It has a low color index (4 to 6 vol.% mafic crystals), but may look darker due to ovoid feldspar phenocrysts that are dark gray in fresh samples. These feldspars are variably mantled by plagioclase (Price et al., 1996). Mafic phases include ferroedenitic hornblende and Fe-rich biotite altered to chlorite and clays (Hogan and Gilbert, 1995). The rock also contains hematite and minor ilmenite. Accessory phases of zircon + apatite ± titanite ± fluorite ± allanite occur in glomerocrysts of mafic minerals and oxides and as inclusions within the feldspar phenocrysts and the mafic minerals.

Diabase

There are two exposed diabase dikes in the area covered by the map (Figure 2). These do not provide the best exposure of diabase, nor do they provide great insight as to the timing and nature of dike intrusion – again, the reader is referred to Stop 5. The exposures in this area, however, speak to the relative abundance of the dikes in the Wichita Mountains – more so when one considers that there are many more hidden dikes than visible ones.

Diabase is a dense, hypabyssal (subvolcanic) basalt. The diabase dikes in southern Oklahoma are characterized by a fine-grained, aphyric texture composed of subparallel plagioclase laths and interstitial augite and magnetite. Like other outcrops that have not been recently cut, quarried, or mined, the exposures here are extensively altered to clay minerals.

Additionally, as seen here, diabase dikes are easily obscured by their propensity to form weathered trenches filled with detritus. The easternmost of the two dikes is a poorly exposed topographic depression trending 010. It intrudes the Mount Scott Granite on the flanks of the hill east of the parking lot and north of the highway.

A second dike is located on the north side of lower Little Medicine Creek canyon, south of the highway. This consists of two entrenched exposures initially described by Gilbert and Powell (1988). The larger exposure is highly weathered but clearly exposed adjacent to the creek. Intact but highly weathered, the diabase is a green-brown, moderately friable rock that occupies a 7-m-wide trench. The trench's walls of Mount Scott Granite are inclined, and the eastern wall preserves an average attitude of 045 55° SE. Given the width of the trench and the dip value, the dike has a true thickness of ~5.7 m. The diabase is exposed adjacent to the creek, but variable weathering makes the entrenched outline of the dike visible to the north and south of the exposure. Although covered in detritus, the trench trends 035 for 100 m uphill. The trench also continues south of the creek, but disappears under the Post Oak surface within 20 m. The Post Oak surface appears to be thicker over the dike, indicating that the erosional trench may be Permian. The second exposure described by Gilbert and Powell (1988) is thinner (0.5 m wide) and poorly exposed. It trends ~ 090 on the boundary between the rhyolite and granite. This dike trend is best marked by a line of vegetation on an east-facing slope to the creek, southwest of the quarry. Largely obscured by soil and detritus, exposures are confined to a mining exploration pit at the contact with the Post Oak Conglomerate (Figure 2). This feature presumably continues to the west for another 50m under the Post Oak and intersects the trend of the larger trench. The attitude of both exposures as expressed topographically is nearly coplanar, and these two exposures may represent two cuts through the same inclined body. However, the thickness of the 090-trending exposure is less than anticipated given the thickness of dike in the larger exposure.

PERMIAN COVER

Post Oak Conglomerate

In contrast to the shabby exposure of the preceding units, the quarry and adjacent roadcut at Quetone Overlook provides one of the best exposures of this Permian sedimentary rock (Figure 3). The conglomerate generally mantles topography on low-relief areas and slopes throughout the Wichita Mountains, but cut exposures are few. The view to the south reveals the more typical expression of this unit – a grass-covered mantle that covers the Cambrian strata. The quarry, however, reveals the nature of the granite facies as seen in and around the Mount Scott Granite, the material that mantles Jed Flat. Within the post Oak Conglomerate cobble composition varies in conjunction with the nearby source – the granite facies is located adjacent to the granite exposures. The clasts here are Mount Scott Granite.

The Post Oak is conglomeratic, characterized by 15- to 65-cm-diameter ellipsoidal to round boulders that are as large as 1 m in places (Gilbert and Powell, 1988) and 1- to 7-cm pebbles. Throughout the granitic facies, boulders are predominantly medium-grained granite, with some coarse granite, metarhyolite, and rhyolite. At this location, the boulders are entirely Mount Scott Granite (Gilbert and Powell, 1988) and are set in a matrix of sand-sized granite lithics, quartz, and microperthitic feldspar, and silt (Al-Shaieb et al., 1980). It is likely that the clasts are sourced from the adjacent highlands. The long axes of the clasts are oriented parallel to bedding, implying fluvial deposition (Gilbert and Powell, 1988). The matrix shows horizontally stratified color changes of light orange and gray-green; gray layers are generally finer grained than orange layers and may be free of large clasts.

The Permian unconformity at the unit's base is marked by the quarry floor and is exposed in section along the adjacent road cut (Figure 3). The underlying rock is extensively fractured and weathered adjacent to the contact, perhaps representing a weakly-developed R soil horizon or similar paleosurface feature. The weathered igneous rock is overlain by a thin layer of arkosic sediments that are in turn overlain by conglomerate. In places, the underlying rock is demonstrably Mount Scott Granite, but much of it is fractured and bleached, and deformed. In other places, Finegan and Hanson (this guidebook) have noted examples of rhyolite cataclastites and breccias. Much of the rock eludes classification, as it is deformed or altered beyond recognition.

Significance

The juxtaposition of the igneous and meta-igneous units at the Quetone Overlook provides important constraints on the emplacement of the Mount Scott Intrusive Suite. The stop also illustrates the nature of Permian sedimentation and recent erosion in the Wichita Mountains.

The rocks adjacent to the highway are altered and possibly highly deformed. The eastern lowlands follow an east-west trend shared by linears and joint sets in the granite. Some have suggested that Quetone is cut by faulting. Gilbert and Powell (1988) noted the intensity of fractures suggested that the "wedge-shaped" rhyolite outcrop results from ver-

Figure 3. The nonconformity between the Mount Scott Granite and the Post Oak Conglomerate. The uppermost granite is extremely weathered. The overlying Post Oak is an arkosic sandstone overlain by a matrix-supported boulder conglomerate, typical of the granite facies of this unit. The compass rests on an example of one of the larger clasts.

tical offset. Finegan and Hanson (this guidebook) conclude that lower Little Medicine Creek follows a fault system that parallels other similar features to the south, on Fort Sill. They however interpret the vertical offset to be minor.

The age of the deformation features is unconstrained, as is the likelihood of vertical offset. But if the vertical offset is indeed negligible, then the entirety of this locality is representative of the igneous section. If so, the rocks here give clues to the nature of the intrusive suite's base and the intrusion's effects on adjacent lithologies.

This stop description and Price (this guidebook) interpret this area to be at the base of the Cambrian Mount Scott intrusive suite, near the local southern margin of the intrusion. The elevations are comparable to basal contacts with the Glen Mountains Layered Complex further west in the central lowlands (following the east-west trend mentioned above). The elevations are comparable to Rush Lake granite to the east, in and around the village of Medicine Park. The nearby peaks indicate a substantial granite section above this location.

Other workers disagree. Gilbert's (1982) places the rocks exposed here near the base of the Mount Scott intrusive suite, but advocates for a more complex geometry. His cross sections to the immediate east characterize the Little Medicine Creek valley as an erosional window through the irregular (folded or undulating) base of the Mount Scott Granite. In contrast, Finegan and Hanson (this guidebook) place the rocks at Quetone within the middle of the Mount Scott Granite. This requires the granite base to have a southward apparent dip of ~50°, but produces a section consistent with the regional interpretation documented Ham et al. (1964).

The regional igneous stratigraphy indicates a superposition of rhyolite on granite on mafic rocks, evidenced by subsurface penetrations and surface exposures (Ham et al., 1964; Powell et al., 1980). The Mount Scott intrusive suite is a tabular body 0.5 km thick emplaced along the unconformable boundary between Glen Mountains Layered Complex (GMLC) and the Carlton Rhyolite Group (Hogan and Gilbert, 1995, 1997; Hogan et al., 2000). This boundary served as a crustal magma trap - a weak zone that permitted near-horizontal intrusion (Hogan et al., 1998). The Mount Scott Granite's subhorizontal contact with the GMLC is seen along the northern slope of the high peaks to the west and presumably extends as an inclined sub-planar contact under the high peaks to its exposure in the central lowlands about 7 km west-southwest of here. This contact can be seen north of Stop 8.

North of Stop 8, the base of the intrusive suite is Mount Scott Granite, one of four lithodemic units that comprise the Mount Scott Intrusive Suite. At Quetone Point, the

Mount Scott is seen in contact with another unit in the intrusive suite, the Rush Lake Granite. Whereas the Mount Scott Granite is widely distributed, the Rush Lake Granite is restricted to the eastern lowlands. Here, this less-voluminous unit comprises the pavement north and east of the parking lot. The Rush Lake and Mount Scott Granites are presumably continuous under Post Oak to the exposures on the western edge of Jed Flat. Although the Rush Lake Granite is somewhat topographically lower than the Mount Scott Granite at its type locality, their elevations overlap at Quetone Overlook, indicating an almost vertical contact.

Field relations coupled with petrological evaluation reveal that the Rush Lake Granite is consanguineous with the Mount Scott Granite and represents a fractionated forerunner of the latter magma (Price, this guidebook). The Rush Lake is included as xenoliths in the Mount Scott Granite here and elsewhere. Whereas this relationship argues that the Rush Lake Granite is relatively older, interdigitating contacts noted on the western edge of Jed Flat suggest both deformed plastically during emplacement. These relations indicate that the Rush Lake Granite preceded Mount Scott Granite but not by any great length of time. At Quetone Point, the still-cooling Rush Lake Granite body could have been shouldered aside by the intrusion of the Mount Scott Granite, producing vertical contacts.

North of Stop 8 the floor of the intrusive suite is GMLC, but at Quetone Overlook the floor is rhyolite. Both the Davidson Metarhyolite and the Fort Sill Carlton Rhyolite have been thermally altered, although the latter's alteration is subtle and less extensive. The Carlton Rhyolite is exposed in the incised valley of lower Little Medicine Creek, giving it a triangular outcrop pattern on the map (Figure 2). Gilbert and Powell (1988) noted the rhyolite outcrop geometry and that it and the adjacent rocks are highly fractured and brecciated. Because of this deformation, they suggested the rhyolite roughly outlines a fault-bounded wedge. But observable contacts between the rhyolite and adjacent units are few and sufficiently ambiguous as to neither support nor discount a faulted relationship. Fractures are pervasive in all of the units here. They are more pervasive in the outcrops adjacent to the highway, where there is evidence of brecciation and cataclastic deformation (Finegan and Hanson, this guidebook). The age of the deformation is unconstrained, although a Pennsylvanian age is likely. The Wichita Mountains result from Pennsylvanian age orogenesis (Soreghan et al., 2012) and record numerous examples of late Paleozoic deformation, particularly in the Slick Hills. It is curious to note however that the rhyolite is largely confined to the lower Medicine Creek valley (below 1550 ft or 473 m), placing it largely beneath the granites exposed on both sides of the valley. Furthermore, the rhyolite is thermally altered, indicating that it was proximal to an intrusion. Both observations are consistent with a rhyolite that is not greatly perturbed by vertical offsets, and that it is more-or-less in place with respect to the Mount Scott intrusive suite at this location.

Whereas the Carlton Rhyolite is subtlety altered, the Davidson Metarhyolite is clearly a hornfels of an alkali-feldspar-rich fine-grained rock. M. Charles Gilbert and coworkers (e.g., Gilbert and Powell (1988) and Miller et al. (1986)) proposed the hornfels is part of the Carlton Rhyolite. While this is likely, current evidence suggests it is not metamorphosed Fort Sill Carlton Rhyolite but instead is a separate Carlton unit (Finegan and Hanson, this guidebook). Davidson outcrops are generally stratigraphically equivalent to the Fort Sill Carlton Rhyolite, but observable contacts between rhyolite and metarhyolite are few in number and ambiguous in nature. Texturally, the Davidson is predominantly aphyric, lacking the ubiquitous feldspar phenocrysts (or alterations thereof) seen in the Fort Sill Carlton. Recrystallization textures are not so extensive as to permit the wholesale obliteration of the phenocrysts from most of the rock. Although the rhyolite is grossly geochemically similar to the Fort Sill Carlton Rhyolite, Finegan and Hanson (this guidebook) note several differences in those trace-elements immune to modification by weathering and alteration. Lastly, the Davidson is much more pervasively recrystallized than the adjacent Fort Sill Carlton Rhyolite. Given that both have similar compositions and that both are proximal to each other and to the granite (*i.e.,* experienced similar thermal conditions), this attribute may indicate that the Davidson protolith was relatively enriched in water, speeding alteration kinetics. Perhaps this wetter unit was a weathered rhyolite locally mantling the Fort Sill Carlton Rhyolite, given that most outcrops of the former are at relatively higher elevations.

If the rhyolite and metarhyolite exposed here are immediately beneath and the base of the intrusive suite, then granite intrusion locally cut upsection from the rhyolite-GMLC unconformity noted regionally. The discordant geometry need not be nonhorizontal nor does it require deviation from the general nature of the crustal magma trap scenario proposed by Hogan and coworkers (Hogan and Gilbert, 1995, 1997; Hogan et al., 1998). The GMLC unconformity was undoubtedly an irregular surface, whereas magma fracturing related to the intrusive suite would propagate more-or-less horizontally which may locally put it above (or even below) the boundary between the rhyolite and the underlying mafic rocks.

The Permian Post Oak takes us from the Early Cambrian to the Leonardian stage of the Permian, some 240 million years later. At that time, the igneous rocks of the aulacogen rift system were regionally on the upthrown and eroded block. The Post Oak Conglomerate formed in valleys and along outwash plains, and its current outcrop pattern reflects the paleodrainage of the Permian landforms. Its occurrence on modern slopes and flats indicates that the current erosion profile for the Wichita Mountains may not be substantially different from that of the Permian.

The Quetone Overlook also preserves evidence of recent erosion processes. The Post Oak Conglomerate armors the flats and impedes the fracture-control stream incisement so dominant in the Cambrian rocks. The conglomerate is the thickest hydraulically conductive unit exposed within the lowlands, and water transport through this unit is evidently substantial. Rainfall percolates through this conglomerate and seeps out along the contact between its contacts with the underlying crystalline rocks. As a consequence, the conglomerate mantled topography contains few incised channels.

SUMMARY

The Quetone Overlook provides significant exposure of both the base of the Mount Scott Intrusive Suite and the Permian unconformity. Although highly fractured and weathered, careful observation reveals that two of the intrusive suite's units, the Rush Lake and the Mount Scott Granites exploited a local horizon through the Carlton Rhyolite Group. This horizon is upsection of the more typical intrusive suite floor of mafic rock, principally the Glen Mountains Layered Complex. Despite this, it remains consistent with the general model of a crustal magma trap for aulacogen intrusion. The intrusion altered two units within the Carlton Rhyolite Group; it weakly altered the Carlton Rhyolite typical of the Fort Sill region and more pervasively altered a separate unit, now mapped as the Davidson Metarhyolite. Erosion exposed all of these materials by the Permian, which is marked by the Post Oak Conglomerate. The conglomerate, uniquely sectioned here by quarry and road cut, was locally sourced fluvial material deposited on weathered granite. Here and elsewhere, the conglomerate preserves the paleotopography of the Permian landforms.

ACKNOWLEDGMENTS

Dr. M. Charles Gilbert of the University of Oklahoma introduced the author to this stop and provided the framework for investigation. Further insights were shaped by Dr. John P. Hogan of the Missouri University of Science and Technology. Additional thanks go to Matthew Ledvina of the University of Texas for pointing out that the two exposures of diabase south of Highway 49 are potentially coplanar. The author thanks and fondly remembers the late Herr Professor Doctor H.G. Huckenholz, Universität München, who kindly joined the author on several early mapping efforts related to this stop. The author is also indebted to Dr. Neil Suneson for his editing and organization of this guidebook.

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Stop 8. Burford Lake geology interpretive trail, eastern Wichita Mountains

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Location: Trail follows along east side of Burford Lake on south side of OK Hwy 49 ~3.3 mi west of intersection with OK Hwy 115 and 2.5 mi east of road to Refuge Headquarters, Comanche County, Oklahoma. E½ W½ NE¼ sec. 21, T. 3 N., R. 14 W., Quanah Mountain 7.5' quadrangle. UTM coordinates: 529920E, 3842290N.

INTRODUCTION

The Wichita Mountains Wildlife Refuge (WMWR) is one of Oklahoma's most popular recreation areas for a number of reasons – the excellent camping facilities, opportunities to hike, rock climb, view wildlife (bison, longhorns, prairie dogs) and scenery, to mention a few. The Wichitas also offer an outstanding opportunity to educate the public about the region's geology. Fortunately, that geology is not only well understood but well exposed.

The Burford Lake Trail is the only geology interpretive trail in Oklahoma. It was developed as a result of a unique cooperative effort between petroleum industry professionals (the Red Earth Desk and Derrick Club of Oklahoma City), state geologists (the Oklahoma Geological Survey and the ConocoPhillips School of Geology and Geophysics at the University of Oklahoma), and federal government naturalists (U.S. Fish and Wildlife Service) to showcase the area's geology and enhance the public's outdoor experience in the refuge. It is the hope of these organizations that the effort will serve as a model for others who want to develop similar interpretive trails in other natural areas in Oklahoma and elsewhere.

THE RED EARTH DESK AND DERRICK CLUB OF OKLAHOMA CITY

The Red Earth Desk and Derrick Club of Oklahoma City (REDD) is a member of the Association of Desk and Derrick Clubs, "a non-profit, international organization whose purpose is to promote the education and professional development of individuals employed in or affiliated with the petroleum, energy, and allied industries and to educate the general public about these industries" (http://www.addc.org/). In early 2011, REDD asked me if I would deliver a "geology lite" presentation at one of their monthly luncheons. I spoke about the spectacular geology of some of the national parks in the western U.S. and the geological principles and history that can studied, in the field, at many of Oklahoma's state parks. Shortly after my presentation, several members of REDD's board asked how they might help in educating the public about Oklahoma's geology. They felt that the success of their companies – the state's energy industry – depends largely on a public who have an understanding and appreciation of the earth sciences.

From the beginning, REDD's goals were centered on 1) earth science education (not necessarily directly related to energy) for the public and 2) getting people outdoors. We agreed that these goals reinforced each other and that a geology interpretive trail (somewhere) would satisfy both goals. Our early discussions focused on what park or recreation area in Oklahoma could be approached with a plan for a geology trail. Three criteria were important: 1) widely visited (i.e., popular); 2) geologically significant; and 3) well-exposed and accessible outcrops. Although not a state park, the WMWR became a prime candidate (1.7 million visitors per year; third most-visited refuge in the U.S.), and preliminary discussions with the staff there indicated they were interested.

WMWR was ideal for another reason – it had been extensively studied by Dr. M. Charles Gilbert at the University of Oklahoma's ConocoPhillips School of Geology and Geophysics (CPSGG), and he was very willing to contribute his expertise to the project. The Oklahoma Geological Survey (OGS) had a cartographic staff with extensive experience doing geologic graphics and who would be able to work on the signs.

BURFORD LAKE TRAIL

WMWR management had several concerns, criteria, and comments regarding geology signs in the refuge. They said that 90% of the visitors to the refuge do not stray far from their cars; therefore, if we wanted the maximum number of visitors to see the signs, we could consider putting them along the roadside. WMWR staff did not want to put signs along trails in their wilderness areas, nor did they want too many signs. The signs had to be low maintenance and vandal resistant. In addition, the refuge's free-roaming bison herd necessitated that the signs be "bison-proof," in other words, robust and resistant to abuse as scratching posts.

In an effort to encourage visitors to see the refuge from somewhere other than inside their car, REDD wanted the interpretive signs to be along a trail, and they asked me to find a short, easily accessible trail that crossed some interesting geology. Luckily, a trail recently "rediscovered" and reopened by Friends of the Wichitas, the Treasure Lake Job Corps, and refuge employees fulfilled all the necessary criteria. It 1) was adjacent to the major east-west road through the refuge, 2) was relatively short, and 3) involved little climbing. It also 4) crossed from the gabbro (Glen Mountains Layered Complex) into the Quanah Granite, 5) passed beneath a dump from an old gold prospect pit, and 6) ended at a scenic overlook above Burford Lake dam. The Burford Lake Trail featured several other aspects of the refuge, including the distribution of soils and vegetation which are thick and relatively abundant on the gabbro but sparse on the granite.

There were some early efforts to coordinate development of the trail with other non-profit organizations that had an interest in the refuge and nearby areas including the Fit Kids Coalition of Southwest Oklahoma, the National Scenic Byway Foundation, and the Medicine Park Museum of Natural Science. However, because the trail was entirely within the WMWR and was being funded privately by REDD, it did not lend itself to being part of other ongoing or future projects.

In February, 2012, REDD formally proposed to WMWR management that geology interpretive signs be designed, fabricated, and placed along the Burford Lake Trail. Funding would be provided by REDD, geological expertise and sign design would be provided by CPSGG and OGS, and installation would be done by WMWR volunteers and staff. REDD would also ask writers from the Oklahoma City Zoo who have a special expertise in public signage to assist with the writing. The proposal was framed as a cooperative project between energy industry employees acting through REDD, geologists working for the State of Oklahoma, and U.S. Fish and Wildlife personnel as caretakers of the refuge. The proposal was accepted and work on the signs began.

SIGN DEVELOPMENT

Dr. Gilbert's and my first chore was to learn what visitors to the refuge wanted to know about the area geology. WMWR staff told us that the most commonly asked geology questions at the refuge are: 1) How do core stones form and are they glacial? 2) Were there volcanoes here? 3) What and where is the Meers Fault? and 4) Is there gold in the Wichita Mountains? The geology along the Burford Lake Trail allowed us to answer three of the four questions; the Meers Fault is outside the refuge and far from Burford Lake.

After walking the trail and seeing its geology, Dr. Gilbert and I agreed that five interpretive signs would be sufficient. WMWR staff wanted to add a sixth describing the history of the lake and dam and "rediscovery" of the trail in 2011 (Figure 1). The geology signs would describe 1) the geologic setting of the refuge as a failed rift (Figure 2); 2) the gabbro as a dark, SiO_2-poor rock (Figure 3); 3) the vegetation's relative abundance on the gabbro and scarcity on the granite (Figure 4); 4) the Wichita Mountains gold rush (Figure 5); and 5) the fractured, light-colored SiO_2-rich granite eroding into core stones (Figure 6). We would also have two small signs; one would point out the core stones that are used as a border along the trail and another mounted on relatively fresh Quanah Granite.

The exact language used on the signs went through many revisions, as did the graphics. Non-geologists reviewed and commented on unclear, confusing, or unfamiliar geological and scientific terminology. For example, the words "silicon dioxide" were substituted for the chemical formula "SiO_2." As the text and graphics for the signs evolved, a number of issues arose and were solved or put off to the future.

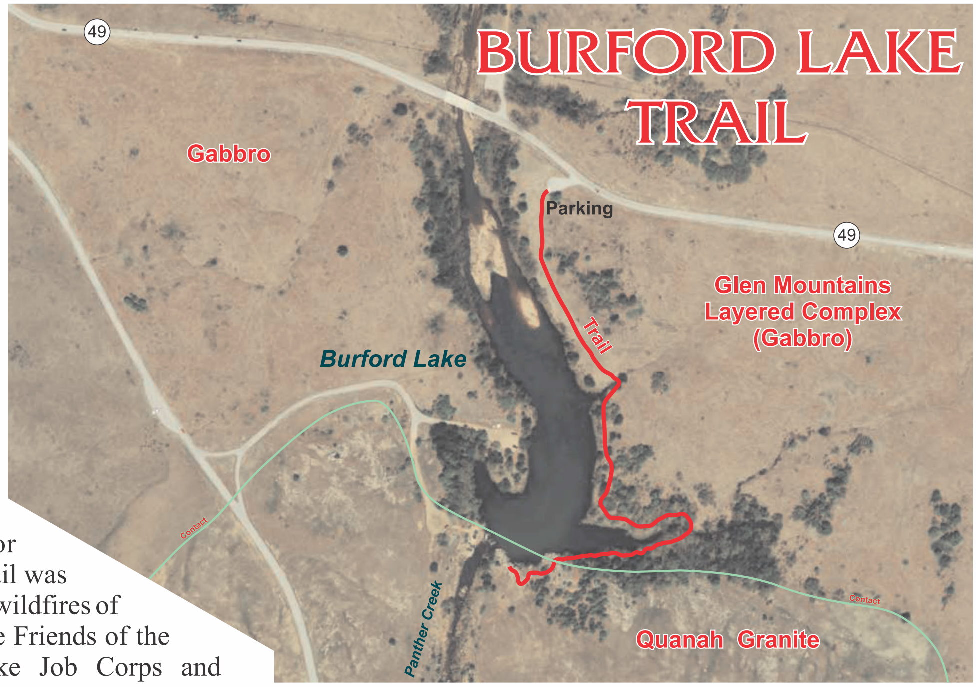
1) At WMWR staff suggestion, some text to support the refuge mission was added.

2) Information on area ecology was included.

3) We considered publishing pamphlets or trail guides with more detailed information. Everyone involved agreed that this could be done in the future.

4) We proposed making trail information accessible by smart phones. Again, this could be accomplished in the future.

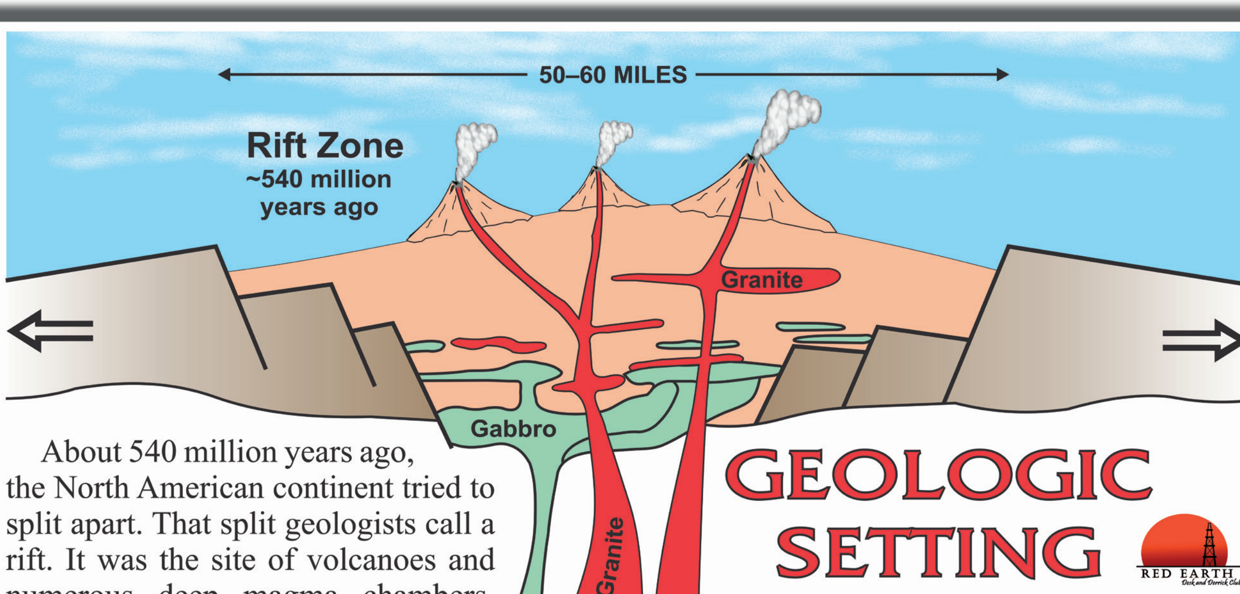
5) Copyright permission for some of the graphics was secured where necessary.



In the late 1920's, the citizens of Cache, Oklahoma contributed funds to build what was then called Panther Creek Dam. About twenty years later, the lake was named to honor Judge Frank B. Burford, one of Oklahoma's outstanding conservationists. The original trail was built in the mid 1930's by the Civilian Conservation Corps, but never made it on the map and was virtually forgotten for many years. Burford Trail was "rediscovered" after the wildfires of 2011 and restored by the Friends of the Wichitas, Treasure Lake Job Corps and Refuge employees in celebration of National Wildlife Refuge Week. Along this trail you will see the two main rocks that are in the Refuge – gabbro and granite.

Help - Over 1.6 million people visit the Wichita Mountains Wildlife Refuge annually. Trash spoils the view and threatens wildlife that eat or become entangled in gum, plastic bags and fishing line. Picking up litter is one way you can help keep the Refuge beautiful and safe.

RED EARTH

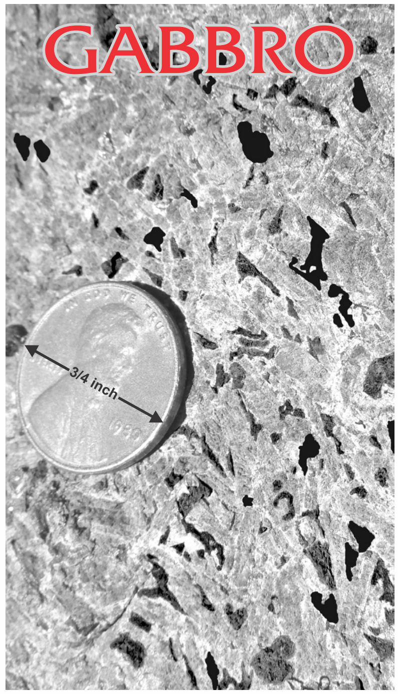


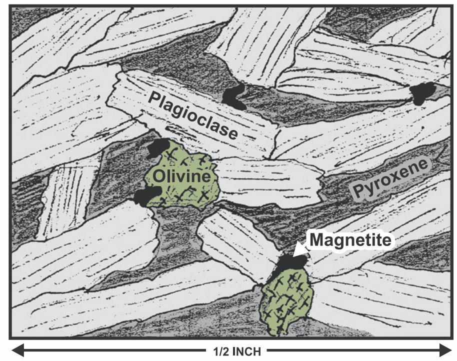
GEOLOGIC SETTING

RED EARTH

About 540 million years ago, the North American continent tried to split apart. That split geologists call a rift. It was the site of volcanoes and numerous deep magma chambers. Over time most of the volcanoes eroded away and the old rift was covered by limestone deposited in an ancient ocean. About 310 million years ago, the area was uplifted during the Ouachita – Arbuckle – Wichita mountain-building period, and more erosion occurred. What we are left with are the roots of the volcanoes – the magma chambers that fed them. Like other rifts throughout the world, the long-solidified magmas are of two very different types – gabbro and granite. We will see both of these on our walk through time.

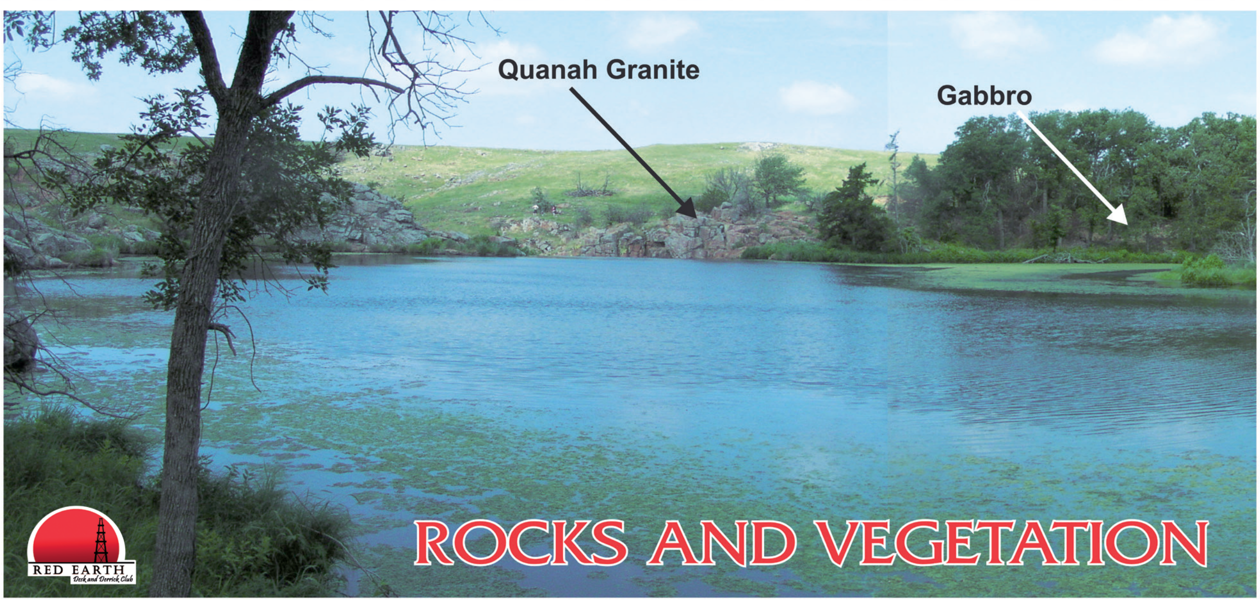
One of the main rock types in the refuge is this dark-colored rock known as gabbro. Look closely at it. You can see individual crystals of the dominant minerals pyroxene (dull black) and plagioclase (gray) and the less abundant olivine (forming pits in the rock) and magnetite (shiny black and sticking up). The large crystal size indicates the magma cooled slowly deep underground, allowing the crystals to grow. If a magma with the composition of gabbro erupts on the surface, geologists call the rock that results basalt. The volcanoes on Hawaii are basalt, and Black Mesa in the far northwest corner of Oklahoma is capped by basalt. Gabbro (and basalt) contain about 50% silicon dioxide (SiO_2) – compare this with the other igneous rock we'll see up the trail.





Animals can be difficult to see. Their lives often depend on staying concealed. Use all your senses to find signs of animal activity. Teeth marks on trees, fallen antlers, nests, scat and animal tracks all point to the presence of wildlife. Quick movements and noise scare away most wildlife. Being quiet will improve your chances of seeing and hearing animals.

RED EARTH Desk and Derrick Club



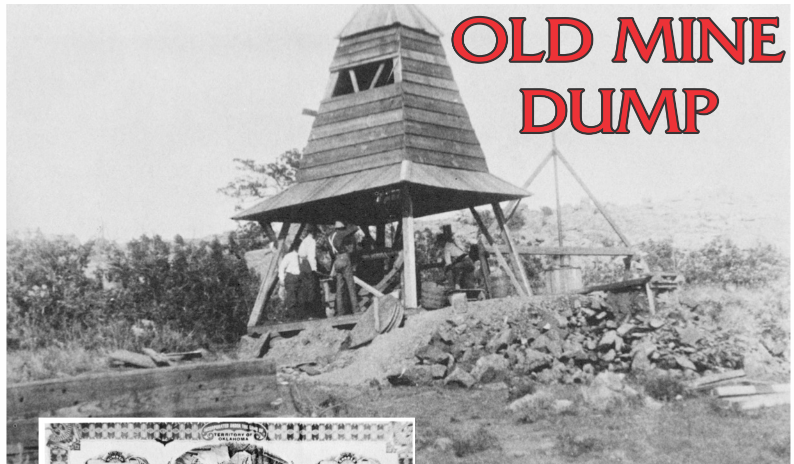
Look across the lake from this vantage point. Do you see the bare rock that forms the bluff and supports the dam for Burford Lake? Notice how light-colored it is compared to the gabbro along this part of the trail. That is the Quanah Granite. Look to the right and notice how much vegetation and how little rock there is along the edge of the lake. Throughout the refuge, pinkish granite typically forms the rugged, rocky uplands, and gabbro forms the flatter, more vegetated lowlands. The gabbro weathers faster and forms a more nutrient-rich soil than the granite, which forms a gravelly sand. Thus, much of the ecosystem in the Refuge depends on the underlying rock type – granite or gabbro.

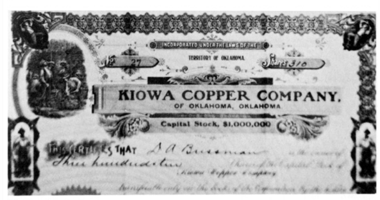
Wetlands are a vital link between land and water. Found along the water's edge, wetlands attract a variety of wildlife. Animals come to drink, hunt for fish or amphibians and cool off. Birds nest in dense shrubs and catch insects buzzing on the waters surface. Tracks in the mud indicate recent visitors, including bison, elk, beaver and birds.

OLD MINE DUMP

"Gold" Mines

Between 1901 and 1907, thousands of gold seekers rushed to the Wichita Mountains with dreams of riches. Claims were staked, mines sunk, mills were built, and mining camps established throughout the area on what was then National Forest land. But only minor amounts of copper, lead, and silver were reported, and the camps were quickly abandoned. The U.S. Geological Survey analyzed 71 samples from the mines and concluded they showed a "uniform absence of even a trace of gold." On the hillside above, one can see a "mine dump" consisting of the rocks dug and blasted out of one of the many unsuccessful mines during Oklahoma's only gold rush.





Photos © University of Oklahoma Press

Lichens are colorful patches on the boulders and rocks. Lichen is actually two plants, a fungi and algae growing together. Their tiny roots absorb minerals from rocks and eventually the boulder breaks into soil which nourishes other plants. Lichens are good indicators of air quality and will die if the air is polluted. Many specimens no bigger than your hand are hundreds of years old.

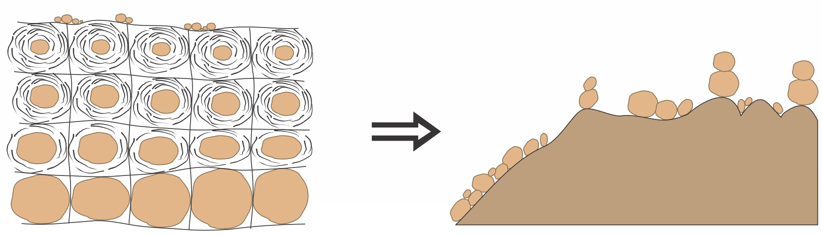
RED EARTH Desk and Derrick Club

END OF THE TRAIL

Fractured Granite

From this view, you get a good idea of what the Wichita Mountains high country looks like. The second principal rock in the refuge is granite which is made up mostly of orthoclase (pink) and quartz (clear). This granite contains almost 75% SiO_2; interestingly, rifts worldwide contain low-silica rocks (like gabbro) and high-silica rock (like granite) with little in between. Note how the rock appears to be broken up into huge blocks along what geologists call "fractures." Weathering processes round the sharp corners, ultimately resulting in spheroidal boulders called "core stones."

Also observe the surrounding topography. After the Wichitas were uplifted about 310 million years ago, parts were eroded down to what we see now. These surfaces are the same as what was walked on by Permian amphibians and reptiles 275 million years ago, before dinosaurs existed. Then this area was completely covered by Permian sediments and is now being uncovered.



RED EARTH Desk and Derrick Club

In September 2013, REDD contracted with Wilderness Graphics in Tallahassee, Florida to produce the signs. WMWR staff recommended Wilderness Graphics, having worked with them previously and knowing that the signs and bases would match other interpretive signs in the refuge. In January 2014, the signs were delivered to the WMWR. On May 3, 2014, a well-attended ribbon-cutting ceremony was held at the trail head. Representatives from the WMWR, REDD, OGS, and CPSGG attended, gave some brief words, and were the subject of numerous photographs. In addition, a number of U.S. Army personnel from nearby Ft. Sill were present; these soldiers are Refuge volunteers and were largely responsible for installing the bison-proof signs.

CONCLUSION

This project was a first for all involved. From my perspective, the most difficult aspect was explaining complex geological phenomena in an easily understood, *but accurate*, way for those visitors interested enough to walk the trail. In addition, this was a "volunteer" job for all of us – it was not something dictated by management of the involved parties. The members of REDD, the geologists and cartographers at the CPSGG and OGS, and the WMWR staff recognized the value of educating the public about one aspect of Oklahoma's geology in an outdoor venue and that it involved working with individuals with different backgrounds and priorities. Considering that the project took almost 2½ years from conception to completion and involved changing staffs, budgets, and work schedules (not to mention a government shutdown), some may find it amazing that it was completed at all. The signs reflect patience and a commitment to educating the public about one aspect of Oklahoma's fascinating geology.

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