Preliminary Geologic Map of the Church Mountain Quadrangle, Lincoln County, New Mexico

By

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Open-file Digital Geologic Map OF-GM 215

Scale 1:24,000

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PRELIMINARY GEOLOGIC MAP OF THE CHURCH MOUNTAIN 7.5-MINUTE QUADRANGLE, LINCOLN COUNTY, NEW MEXICO

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Cover photo: View of Church Mountain (broad tree-covered hill, middle ground just right of center) from the south. Sharper peak, with low rock outcrops, at the end of the grass-covered ridge in front of Church Mountain is Gaylord Peak; rock outcrops are of the flow of Gaylord Peak. Mountain in the distance and left of center is Carrizo Peak.

Comments to Map Users

A geologic map displays information on the distribution, nature, orientation, and age relationships of rock and deposits and the occurrence of structural features. Geologic and fault contacts are irregular surfaces that form boundaries between different types or ages of units. Data depicted on this geologic quadrangle map may be based on any of the following: reconnaissance field geologic mapping, compilation of published and unpublished work, and photogeologic interpretation. Locations of contacts are not surveyed, but are plotted by interpretation of the position of a given contact onto a topographic base map; therefore, the accuracy of contact locations depends on the scale of mapping and the interpretation of the geologist(s). Any enlargement of this map could cause misunderstanding in the detail of mapping and may result in erroneous interpretations. Site-specific conditions should be verified by detailed surface mapping or subsurface exploration. Topographic and cultural changes associated with recent development may not be shown.

Cross sections are constructed based upon the interpretations of the author made from geologic mapping, and available geophysical, and subsurface (drillhole) data. Cross-sections should be used as an aid to understanding the general geologic framework of the map area, and not be the sole source of information for use in locating or designing wells, buildings, roads, or other man-made structures.

The map has not been reviewed according to New Mexico Bureau of Geology and Mineral Resources standards. The contents of the report and map should not be considered final and complete until reviewed and published by the New Mexico Bureau of Geology and Mineral Resources. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the State of New Mexico, or the U.S. Government.

INTRODUCTION

As a part of on-going investigations into the water resources of the Sacramento Mountains and the Tularosa basin, geologists and contractors with the StateMap program of the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) have been mapping the general geology of the USGS 7.5-minute quadrangles encompassing these regions. Lying at the north end of the Sacramento Mountains, the Church Mountain quadrangle was mapped in the 2010-2011 season at a scale of 1:24:000 to collect the geologic data needed for accurate water resource assessment, as well as to improve upon the resolution and detail of existing maps of the area. The data collected may also be useful to mineral exploration, as the area contains known metal ore resources, and to regional geologists, as we, as well as Kelley et al. (2011) and Goff et al. (2011), have acquired new geochemical data on the volcanic rocks of the area, and have submitted samples for geochronology, the results of which will appear in subsequent versions of the report. Below is a summary of observations on the quadrangle, as well as an overview of previous work in the area, and discussions of possible geologic controls on ground water flow through the area.

ACKNOWLEDGEMENTS

We would like to thank Mark Hendricks of the I-Bar-X Ranch (Carrizozo, NM) and Omar Barnes of the Diamond Peak Ranch (Nogal, NM) for granting us access to their ranches, as well as Bryce Duggar for allowing us to use his roads to access Tortolita Canyon from the east. We also thank the Lincoln National Forest for granting a special access permit to continue field work during severe fire restrictions. Cathie Eisen was instrumental in obtaining access by determining landownership status. This project was funded by the StateMap program, which is jointly supported by the US Geological Survey and the NMBGMR. We thank J. Michael Timmons (NMBGMR) for his logistical support. ALS Laboratory Group (Reno, NV) provided the new geochemistry results presented herein. Discussions with Fraser Goff and Rick Lawrence provided many insights into the igneous history of the area. Fraser Goff's thin section work provided much of the petrographic observations mentioned herein. Fieldwork was conducted by standard methods, including stratigraphic traverses and contact walking plotted on USGS topographic maps with the help of GPS and Brunton. Contacts were extrapolated from areas visited on the ground with the help of aerial imagery. All colors reported were obtained with the help of a standard Munsell color chart.

GEOGRAPHY, LAND USE, AND ACCESS

The Church Mountain quadrangle is located immediately southeast of the small town of Carrizozo at the northern end of the Sacramento Mountains. It stretches from around US 380 in the north to the northern flank of Nogal Peak in the south (Figure 1), and from Little Cub Mountain on the west to the eastern flank of Church Mountain on the east. Elevation varies from just over 9470 ft on the north flank of Nogal Peak to just over 5500 ft in the basin in the northwest corner. Vegetation varies from Chihuahuan grassland on the basin floor, to piñon-juniper woodland and forest on the flanks of the Church Mountain highlands, to a mix of high-elevation scrubland, piñon-juniper woodland, and pine forest in the interior of the highlands. There is also very local high-elevation grassland on the south edge of the quadrangle at the highest elevations.

The land is split between Wilderness/National Forest land and large private ranches. The White Mountain Wilderness, a part of the Sacramento district of the Lincoln National Forest, encompasses most of the Church Mountain-area highlands. These lands are used primarily for recreational use, including hiking, camping, hunting, and horseback riding. Numerous trails (of various states of repair) run around this area along several of the canyons and ridges, providing access by foot for camp-based field work as well as reliable paths back to camp after dark. At the time of mapping, most of the lowlands of the quadrangle, including the lower-elevation peak of Little Cub Mountain, lay on the lands of two large private cattle ranches. Additionally, a few small plots of private land lay within and around the highlands, which we suspect were old mining claims turned private land. We accessed these lands only with the express permission of the land owners or ranch managers.

Access to the Church Mountain quadrangle was provided by US 380, numerous ranch roads, and forest roads 400 and 5628, which follow Nogal Canyon and Pennsylvania Canyon, respectively. Hiking trails, particularly those along Tortolita Canyon, Pennsylvania Canyon, and Gaylord Canyon, provided access to the interior of the highlands. Much of the interior of the Church Mountain highlands was mapped from backpacking camps established along Tortolita Creek.

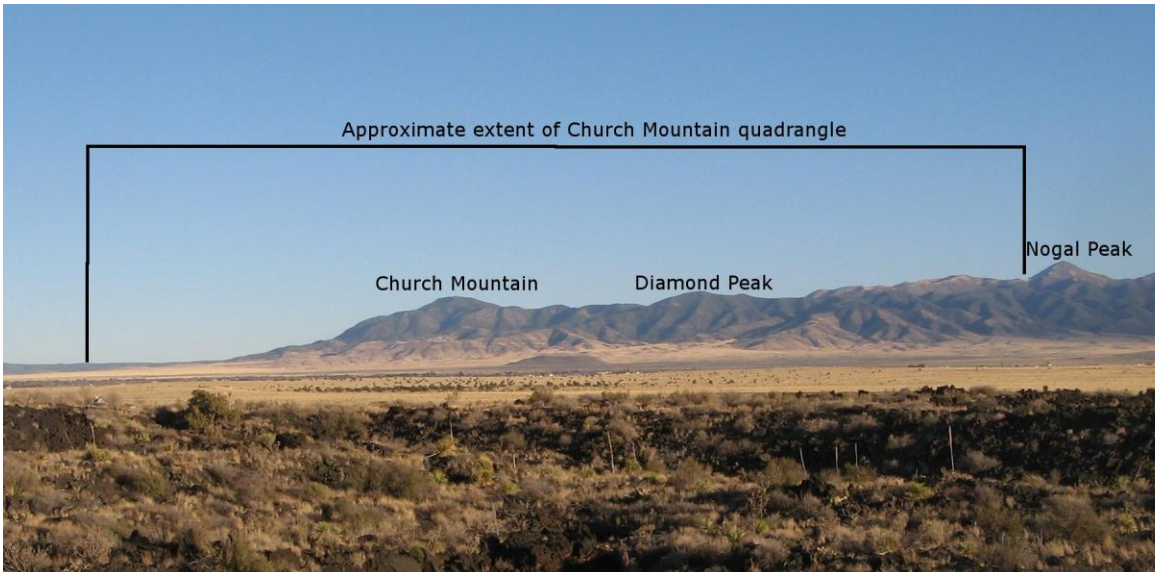

Figure 1 - View of the study area from the Valley of Fires recreational area to the west. The quadrangle stretches from the north flank of Nogal Peak into the basin around US 380 (not visible). The Double Diamond Peaks are the grass-covered, vaguely banded hills in front of (to the west of) Church Mountain. The dark hill in front of the tree-covered highlands between Diamond Peak and Church Mountain lie on the Cub Mountain quadrangle to the west of the study area. Dark blocks in the immediate foreground are basalts of the Carrizozo malpais on the recreational area.

GEOLOGIC SETTING AND PREVIOUS WORK

Geologically, the area lay near the axis of and on the western limb of a broad synclinal basin (Sierra Blanca basin of Kelley and Thompson, 1964; see also Griswold, 1959; Weber, 1964) in which early and middle Tertiary sediments and volcanics accumulated. It includes the apparent northern end of the Sierra Blanca volcanic field, a mid-Tertiary igneous complex generally composed of weakly to moderately alkalic mafic-intermediate flows and minor stocks intruded by large bodies of syenite (cf. Thompson, 1972; Moore et al., 1991; Goff et al., 2011). The quadrangle also contains outcrops of strata as old as upper Cretaceous, usually appearing at the surface where upheld by erosion-resistant felsic intrusions. Today, the Church Mountain quadrangle lay at the eastern flank of the northern Tularosa basin, which is bound on the east by the Sacramento Mountains. As such, it is a recharge zone for the Tularosa basin aquifer system (cf. Rao, 1986; Newcomer and Shomaker, 1991).

Early literature on the area is generally restricted to the mining and economic geology of the area, starting with Jones (1904). General geologic mapping began at the reconnaissance scale with unpublished regional USGS mapping (compiled by Dane and Bachman, 1958), with an early discussion of the general geology included in Griswold (1959). Weber (1964) then mapped the Carrizozo 15-minute quadrangle at a scale of approximately 1:175,000, substantially improving the resolution of existing maps and introducing the term Cub Mountain Formation for the Eoecene sandstones and mudstones overlying the Cretaceous section and underlying the Sierra Blanca volcanics.

Possibly the most important early work on the area, however, was the extensive work of T.B. Thompson (cf. Thompson, 1964, 1966, 1972, 1973), who established the stratigraphic and nomenclatural framework for the volcanic and intrusive rocks of the Sierra Blanca volcanic field. Although Thompson’s work was primarily to the south of the Church Mountain quadrangle, the same stratigraphy can be followed north along the western flank of the Sacramento Mountains onto this quadrangle. Thompson (1966, 1972) established the age range of the Sierra Blanca field to be between ~38 and 26 Ma, with the upper age constrained by a K-Ar date on one of the syenitic stocks. Thompson also established a marked increase in alkali and silica content through time in the igneous rocks, culminating in the syenite and alkali granite intrusions of the Three Rivers stock (see also new geochemical data in Goff et al., 2011, Kelley et al., 2011, and presented herein). His stratigraphic division of the volcanics was fairly simple, dividing them amongst his Walker andesite breccia, Church Mountain latite, Nogal Peak trachyte, and Godfrey Hills trachyte (Thompson, 1966, 1972), with the first encompassing the earlier, more mafic/intermediate and less alkali-rich flows and the latter three being more alkali-enriched and felsic. This stratigraphy remained in use up until the present study; we, as well as Kelly et al. (2011) and Goff et al. (2011) working in nearby quadrangles, present a revised and more detailed, though at present informal, stratigraphy. Thompson (1966, 1972) also established the nomenclature for the syenitic stocks of the Sierra Blanca field (e.g., Three Rivers stock, Bonito Lake stock, Rialto stock), which we use herein.

More recent work in the field area includes that of Lucas et al. (1989), who established the Eocene age of the Cub Mountain Formation, and Cather (1991), who divided the Cub Mountain on provenance grounds into the primarily basement rock-sourced Cub Mountain Formation and the primarily volcanic terrain-sourced Sanders

Canyon Formation. Further south, Moore et al. (1988a, 1988b) studied the intrusives on the Mescalero Apache Indian Reservation, and, along with Thompson, published several reports on the general geochemical and geological evolution of the Sierra Blanca volcanic field (Allen and Foord, 1991; Moore et al., 1991); although well south of the Church Mountain quadrangle, their results are important to the understanding of the region as a whole.

We do not know of any previous detailed studies of the Quaternary sediments on the Church Mountain quadrangle. Several recent reports on the Quaternary of neighboring quadrangles are available, however (cf., Koning, 2010; Kelley et al., 2011; Koning et al., 2011).

Nomenclatural notes

Although Thompson's (1966, 1972) stratigraphy formed the basis for our initial studies of the area, we break from his stratigraphic nomenclature in a few regards, and add several informal units to his Walker unit to facilitate discussion. Thompson proposed the term "Walker andesite breccia" to encompass all the volcanic and sedimentary strata above the Sanders Canyon Formation up to the base of his Nogal Peak trachyte, Church Mountain 'latite', and Godfrey Hills trachyte (the last is not exposed on this quadrangle). Our studies have found that this section can actually be divided into several continuous units, most of which are not breccias, and that the lavas and lava clasts do not have true andesite geochemistries (Figure 2; see also geochemical data in Goff et al., 2011). Hence we drop the 'andesite breccia' and instead simply use 'Walker Formation.' Recent geochemistry has also been obtained for his upper flows, the Nogal Peak trachyte, Godfrey Hills trachyte, and his Church Mountain 'latite.' While samples of the first two generally plotted as trachytes or trachyandesites (see Goff et al., 2011, and Kelley et al., 2011, respectively) and hence keep their 'trachyte' designations, the last plotted as a phonolite (sample CMC-83, Figure 2a); we thus use the term 'Church Mountain phonolite' instead of 'latite,' and note that Allen and Foord (1991, pg. 99) refer to these flows as phonolites as well.

We also note that Thompson's (1966, 1972) Walker unit includes a great variety of flow types and sediments, and hence we propose several informal terms to subdivide the Walker unit in order to facilitate discussion. The basal such unit consists of pyroxene-phyric flows and flow breccias, which we refer to as the unit of Barber Ridge, for exposures along the ridge stretching from the Godfrey Hills to the central Sierra Blanca area. Above that is a section of macroscopic pyroxene-lacking plagioclase porphyries and aphanetic flows interbedded with conglomerates which we refer to as the unit of Rattlesnake Canyon. Above this is a distinctive, strongly flow-foliated (rheomorphic), clast-rich ignimbrite here refered to as the tuff of Argentina Springs, which may correlate to the tuff of Bucky Pasture of Kelley et al. (2011). Above this tuff is another section of lavas and conglomerates referred to here as the unit of Double Diamond Peaks. We note that these terms are entirely informal, but use them as they serve as useful and continuous stratigraphic horizons that likely indicate geologic events and/or changes in the magma system.

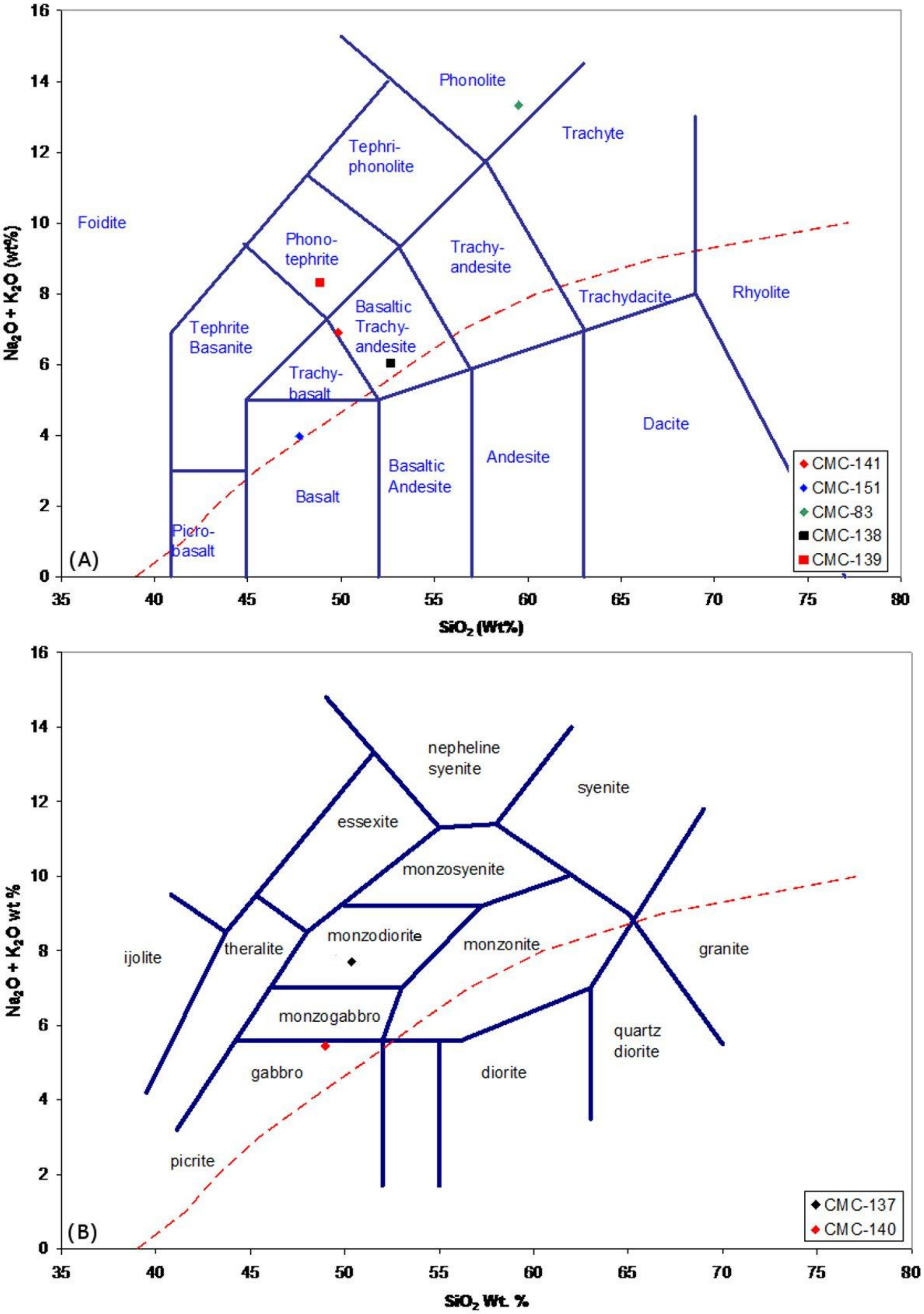

Figure 2 - TAS diagrams of geochemically analyzed samples from the Church Mountain quadrangle. See Table 1 for major element analysis results and locations of samples. Dashed red line on each plot is the alkalic/subalkalic dividing line according to Irvine and Baragar (1971) using control points from Rickwood (1989). A) Le Bas plot (after Le Bas et al., 1986) of volcanic rock samples. B) Cox plot (after Cox et al., 1979, with names adapted from Middlemost, 1994) of plutonic rock samples.

Table 1: Normalized[1] major element contents[2] for analyzed igneous rocks

SAMPLE	CMC-83	CMC-137	CMC-138	CMC-139	CMC-140	CMC-141	CMC-151
Map unit	Tcp	Tipm	Twdf	Twdf	Tidsb	Twrvs	Twbf
Easting[3]	429509	427290	426613	426425	426498	426482	423076
Northing[3]	3712021	3714269	3714320	3714174	3713651	3715108	3710201
SiO2	59.5	50.4	52.6	48.9	49.0	49.9	47.8
Al2O3	20.4	20.3	16.9	18.2	20.6	18.2	16.8
Fe2O3	3.2	8.0	9.4	11.1	8.3	9.7	10.8
CaO	2.0	8.7	8.8	7.9	10.2	7.9	11.0
MgO	0.6	2.5	3.9	3.3	4.0	4.2	7.6
Na2O	7.0	4.6	3.4	4.9	3.8	5.2	3.2
K2O	6.3	3.1	2.7	3.4	1.7	1.8	0.8
TiO2	0.7	1.4	1.5	1.6	1.4	1.8	1.3
MnO	0.1	0.2	0.2	0.2	0.1	0.2	0.2
P2O5	0.1	1.0	0.6	0.5	0.9	1.2	0.6
TOTAL	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
LOI	2.5	3.4	6.4	7.1	7.2	3.8	3.7
C	0.1	0.1	1.1	1.2	1.1	0.3	0.2
S	0.0	0.2	0.0	0.0	0.0	<0.01	<0.01

[1] – Major element contents normalized to sum to 100%

[2] - All values are percentages

[3] - UTM coordinates are for NAD27 zone 13S

We also informally name two flows found toward the top of the volcanic package, as well as three mafic-intermediate intrusions. The flows of Gaylord Peak were apparently originally mapped as a part of the Church Mountain 'latite' by Thompson (1966), but we feel it is lithologically distinct and hence separate the flows from the Church Mountain section. Our flow of Kountz Canyon is another lithologically distinct and mappable flow whose map pattern suggests it was deposited in a canyon incised into the Walker section. We also informally name three mafic-intermediate intrusive bodies (the monzodiorite of Pine Canyon, the alkali gabbro porphyry of Wind Canyon, and the alkali basalt porphyry of Diamond Spring); although these bodies have been recognized and mapped previously (e.g., Weber, 1964), to our knowledge these mafic-intermediate stocks have not received nearly as much attention as the younger syenites and have not been described in detail before. Note that we use the term 'basalt' in its textural context, to indicate the intrusive has an aphanetic matrix.

GEOLOGIC HISTORY

(Refer to correlation chart, Figure 3)

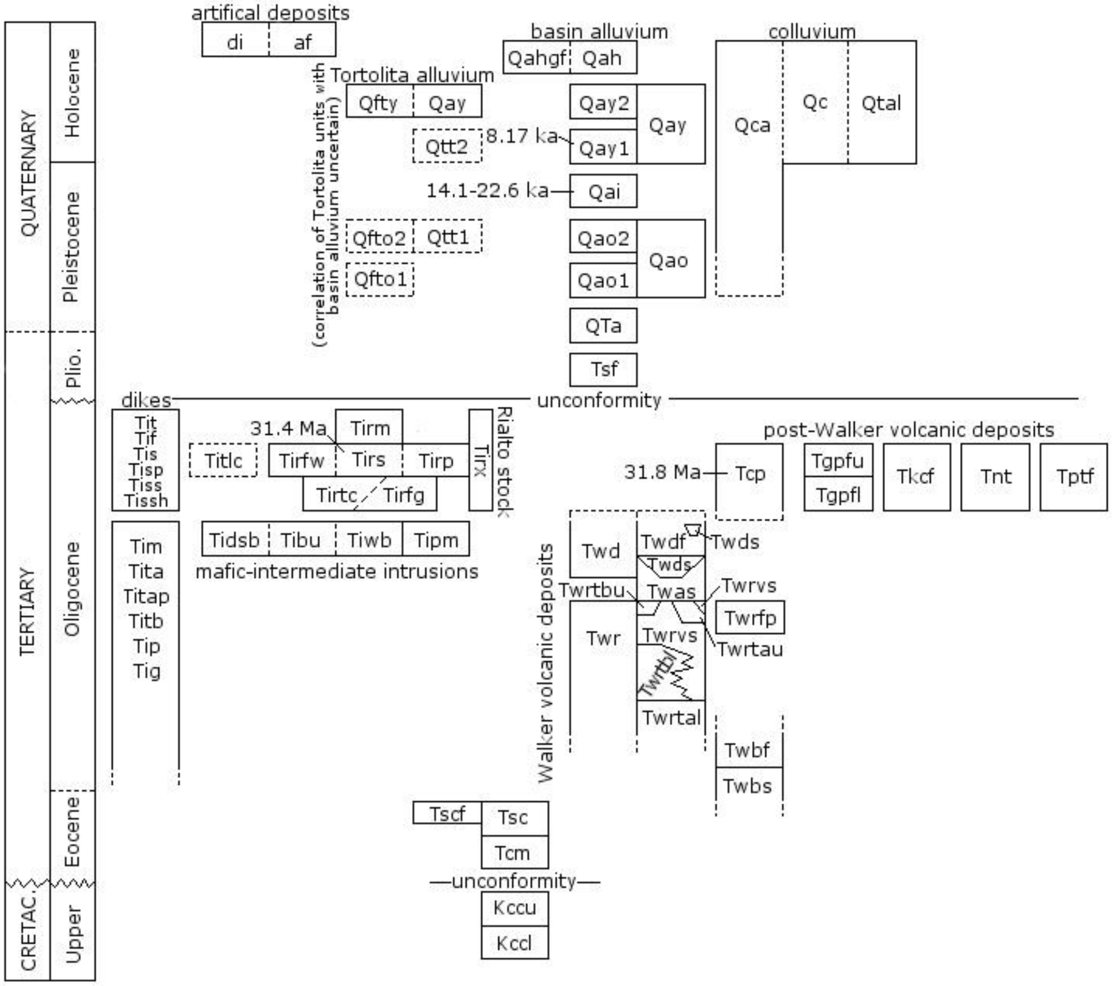

Figure 3 - Correlation chart for map units on the Church Mountain quadrangle. Dashed lines indicate uncertain correlations. Tertiary ages are K-Ar dates, Quaternary ages are radiocarbon dates.

Mesozoic and Eocene sedimentary rocks

The oldest exposed strata on the Church Mountain quadrangle are the fluviatile sandstones and mudstones of the Cretaceous Crevasse Canyon Formation (Kcc) of the Mesaverde Group (Cather, 1991). These are disconformably overlain by sandstones and mudstones of the lower to middle Eocene Cub Mountain Formation (Tcm; Cather, 1991). Cather (1991) noted the two units are lithologically very similar, and suggested locating the contact based on the presence of coarse sandstones, pebbles over 3-4 cm diameter, and/or variegated mudstones. We break from this definition, instead placing the contact on a conspicuous paleosol found at the top of the Crevasse Canyon section marked by 10-

15% irregular purplish black (MnO?) concretions (Figure 4), after Koning et al. (2011). We feel this paleosol serves as an excellent continuous and well-locatable marker horizon that accurately distinguishes the two deposits.

Petrographic studies of the Cub Mountain Formation suggest it records progressive unroofing of Laramide basement uplifts (Cather, 1991). The lower Cub Mountain appears to consist dominantly of recycled Crevasse Canyon fragments, but upsection the proportion of carbonate clasts (presumably from uplifted Paleozoic carbonates) and clasts from 'basement sources' (in this case, granite, gneiss, and quartzose and micaceous metamorphic rock fragments, as well as microline, orthoclase, untwinned plagioclase, and muscovite) increases (Cather, 1991), suggesting progressive unroofing of uplifted source terrains. This progression is abruptly interrupted at the contact with the Sanders Canyon Formation (Tsc), where the abundance of basement-sourced grains drops off and the abundance of volcanic-sourced grains (in this case, volcanic rock fragments, biotite, amphibole, pyroxene, olivine, sanidine, and twinned plagioclase) rapidly increases (Cather, 1991). This shift is located in the field primarily by examining sandstone exposures and noting the proportions of plagioclase, potassium feldspar, quartz, and volcanic and basement lithics, and placing the contact where the volcanic-sourced grains begin to dominate. The exact source of the volcanic grains has not been studied, but may be the Sierra Blanca volcanic field.

Figure 4 - Paleosol developed on top of the Crevasse Canyon Formation. The light green-light gray color, massive sand, and purplish black MnO (?) concretions make this stratum distinctive and relatively easy to map.

Figure 5 - Clast of the tuff of Argentina Springs, showing strong flow foliation, lithic-rich nature, and feldspar phenocrysts.

Latest Eocene(?) to Oligocene igneous rocks

Sierra Blanca Volcanics

The Sanders Canyon Formation is overlain by volcaniclastic conglomerates that coarsen abruptly to cobble and local boulder size, before giving way to pyroxene/plagioclase porphyry lava flows and flow breccias; these are the basal Walker Formation, here referred to as the unit of Barber Ridge (Twb). The conglomerates are poorly sorted and massive, suggesting they were deposited by debris flows from a nearby source. A sample of one of the lava flows (CMC-151) was analyzed for general geochemistry (Table 1) and plots as an alkali basalt on a Le Bas plot (Figure 2a).

Above the pyroxene-phyric flows are pyroxene-aphyric plagioclase porphyries and aphanetic flows as well as reddish-brown matrix-rich conglomerates of the unit of Rattlesnake Canyon (Twr). These lower volcanic and sedimentary units are generally continuous across the Church Mountain highlands, albeit with thickness variations from irregular contacts. Some of the upper flow units in the Rattlesnake Canyon section shrink and pinchout, however, and their distributions may be useful in locating source areas. A sample of an aphyric lava from this unit was analyzed for general geochemistry (CMC-141, Table 1) and plotted as a basaltic trachyandesite on a Le Bas plot (Figure 2a). All conglomerates are poorly sorted and massive, and generally have a dark reddish-brown fine-grained matrix, suggesting they are proximal debris flow to mud flow deposits.

Above the unit of Rattlesnake Canyon is a continuous, lithic-rich, strongly flow-foliated (rheomorphic), plagioclase-phyric ignimbrite (Figure 5), the tuff of Argentina Springs (Twas). In several places, the ignimbrite appears to have a volcaniclastic interval between two flow-foliated ignimbrite intervals, suggesting the tuff erupted in two pulses. This volcaniclastic interval is generally poorly exposed, however, and can be difficult to distinguish from the already lithic-rich tuff on either side of it. This tuff may correlate to the tuff of Bucky Pasture of Kelley et al. (2011).

Lavas and conglomerates of the unit of Double Diamond Peaks (Twd) lay above the tuff of Argentina Springs. Although the poorly sorted and massive conglomerates are similar to those of underlying units, the character of the lavas changes to include plagioclase, plagioclase/pyroxene, plagioclase/amphibole, and rare plagioclase/biotite porphyries whose relative abundances change throughout the area; another significant difference is that locally these flows and the conglomerates appear to fill deep paleocanyons carved into older strata. The plag/pyx porphyries are found only on the northwestern flank of the Church Mountain highlands along Schelerville Ridge, while the rare plag/bt porphyries are only locally found to the south along the same ridge. The plag/amph porphyries appear to dominate the stratigraphy immediately beneath the Church Mountain phonolite on the north flank of Church Mountain, but to the north and west they intercalate with plag porphyries and become increasingly less abundant. Samples of these later two flow types were geochemically analyzed (samples CMC-138 [plg/amph] and CMC-139 [plg], Table 1) and plotted as basaltic trachyandesite and phonotephrite, respectively, on a Le Bas plot (Figure 2a). The interior of the Church Mountain highlands is dominated by plagioclase porphyries. Rugged paleotopography during this time is suggested by apparent deep paleocanyons along the flanks of Diamond and Gaylord Peaks filled by Double Diamond Peaks conglomerates and lavas. The variety of laterally-restricted but intercalated flow mineralogies as well as the presence of rugged paleotopography is a significant break from the characteristics of the lower units.

Above the unit of Double Diamond Peaks are several distinct but laterally restricted flows. The small extents of the flows of Kountz Canyon (Tkcf) and Gaylord Peak (Tgpf) and the Nogal Peak trachyte (Tnt) suggest they may have been restricted to paleocanyons carved into the underlying Walker strata.

The Church Mountain phonolite (Tcp) is another laterally restricted, but very thick (up to ~500 m), unit whose irregular basal contact suggests significant paleotopographic influence. Unfortunately, the basal contact is generally very poorly exposed, due to coarse, thick colluvium being shed by exposed cliffs of the phonolite (Figure 6), but it appears to climb and fall particularly along the flanks of Church Mountain itself, suggesting the unit erupted onto a rugged topography. Local exposures of Church Mountain phonolite-like rock among plagioclase/amphibole porphyry outcrops on the north flank of Church Mountain indicate the basal phonolite and uppermost Double Diamond Peaks flows were coincident in time and at least locally interbedded. The Church Mountain phonolite can be highly variable, but its characteristics are consistent with emplacement as a volcanic dome (Weber, 1964). Weber (1971) obtained a whole rock K-Ar age on a vitrophyre within the Church Mountain sequence of 31.8±1.3 Ma.

The Church Mountain phonolite, Nogal Peak trachyte, and flow of Gaylord Peak each appear minerologically and/or chemically more felsic and alkali-rich than the lower Walker flows (Figure 2a; see also geochemical data of Goff et al., 2011). This is in agreement with the progressive silica and alkali enrichment through time observed by Thompson (1972).

Figure 6 - Cliffs of Church Mountain phonolite above think pile of talus and colluvium. View is of Church Mountain from the northwest.

Sierra Blanca Intrusives

Dikes, sills, and stocks on the Church Mountain quadrangle can be generally divided into mafic-intermediate and felsic. Despite the lack of age control on the timing of the mafic-intermediate intrusions, the former likely predates the later as the data of Thompson (1966, 1972), Goff et al. (2011), Kelley et al. (2011), and presented here all suggest a shift from more mafic to more felsic activity through time in the area.

Mappable stocks of mafic-intermediate composition include the alkali gabbro of Wind Canyon (Tiwg), the alkali basalt porphyry of Diamond Spring (Tidsb), and the monzodiorite of Pine Canyon (Tipm); there are also isolated outcrops of rock similar in texture to the alkali basalt porphyry of Diamond Spring that are interpreted as intrusions even though their contacts are too poorly exposed to establish their intrusive nature (Tibu). Samples of the alkali basalt porphyry and monzodiorite were geochemically analyzed (CMC-140 and CMC-137, respectively, Table 1, Figure 2b); although the former plots as a gabbro on the Cox plot, we prefer to use the term ‘basalt’ due to the rock’s aphanetic matrix. The Wind Canyon and unnamed intrusions are assumed to have a similar chemistry to the Diamond Spring intrusion due to their similar mineralogies and textures. The alkali basalt porphyry of Diamond Spring and the monzodiorite of Pine Canyon both intrude strata as young as the lower flows of the unit of Double Diamond Peaks, and are themselves cut by several mafic-intermediate and felsic dikes.

Mafic-intermediate dikes are also very common to the Church Mountain area. In fact, many more dikes are found on the ground than are possibly mappable at this scale, and the map only shows a handful of the larger and more continuous dikes in the area. Dike orientations are highly variable, but it appears they can be categorized as east-west and radiating. Radiating dikes range in attitude from northeast-southwest to northwest-southeast to north-south (essentially, all trends except ENE-WSW), such that there is significant overlap in trends between the radial dikes and the east-west dikes. The radiating pattern is particularly visible in the dike attitudes along the north to northwestern flank of the Church Mountain highlands, where dike attitudes range from north-northeast to east-west in attitude; northeast-southwest to north-south trending dikes along the southern boundary of the quadrangle probably also belong to this pattern. Dike attitudes appear to radiate from a zone east of Diamond Peak that stretches from just north of the Kountz Canyon-Tortolita Canyon junction in the south to the headwaters of

Pine Canyon in the north. It is probably not coincidental that the lavas and conglomerates of the unit of Double Diamond Peaks that are found in this area are severely bleached and iron oxide-stained, possibly as a result of hydrothermal activity. It is very likely a large mafic-intermediate pluton exists at depth beneath this zone that sourced the dikes and provided the heat and possibly fluids to alter the overlying lavas and conglomerates. The Church Mountain phonolite flows found in the area are not visibly altered, however, suggesting emplacement of the pluton predated eruption of the phonolite. The east-west trending dikes, most apparent south of Tortolita Canyon, have no obvious source or controls on their trends.

Mappable felsic intrusions include the Rialto stock and its various phases and isolated felsic sills upholding hills found well outside the Church Mountain highlands. The Rialto stock (Thompson, 1972) is a north-south elongate series of at least three intrusive phases ranging in composition from syenite to monzonite to quartz diorite (see chemistry data of Goff et al., 2011). The earliest phase, which may itself be the product of two pulses, is recorded as two locally-exposed units, one a coarse potassium feldspar porphyry along the south side of Tortolita Canyon ('syenite porphyry of Tortolita Canyon,' Tirtc in the unit descriptions) and another a fine-grained gray syenite found south of Tortolita Canyon ('fine-grained gray syentite,' Tirfg); the former may intrude the later, but the relationship is not clear. The second phase (Tirs/Tirp, as well as Tirfw), which at this level of exposure is the most extensive, clearly intrudes these earlier phases, and classifies as a syenite both by minerologic criteria and geochemical criteria (Goff et al., 2011). Moore et al. (1991) obtained a K-Ar date on hornblende and biotite of 31.4±1.3 Ma for this phase, essentially equivalent to the K-Ar date obtained on the Church Mountain phonolite by Weber (1971). The third and final recognized phase (Tirm), which clearly intrudes the primary phase both here and on the Nogal Peak quadrangle to the south (Goff et al., 2011), classifies as a monzonite minerologically but as a quartz diorite geochemically (chemical data in Goff et al., 2011). On the quadrangle to the south, it occurs as north-northeast-elongate narrow intrusions; here, it generally occurs in isolated lenticular or irregular bodies.

Felsic sills in Little Cub Mountain (Titlc) and Hughes Hill (Tissh) intrude relatively incompetent Eocene and Cretaceous strata. These hills appear to be upheld by these thick sills resisting erosion.

Felsic dikes have a variety of attitudes, including north-south, northwest-southeast, NNE-SSW, and even east-west. The control on these attitudes is not understood, although one north-south dike appears to collocate with a down-to-the-east normal fault, suggesting a structural control on attitudes. The dikes along the western margin of the quadrangle may be radiating from the syenitic stocks of the Sierra Blanca field.

Latest Tertiary and Quaternary sediments and soils

Buttressed against the volcanic and Mesozoic highlands and filling the basins in the western through northern portions of the quadrangle are Pliocene(?) through recent sediments largely derived from the Sierra Blanca volcanic field. Map pattern and field observations suggest that there is no fault laying at the base of the volcanic highlands, that is, the location of the highlands is stratigraphically controlled and not structurally controlled. The basins formed where less competent strata (the Eocene Cub Mountain and Sanders Canyon Formations) were eroded away and backfilled. This is suggested by rare exposures of the stratigraphic contact between the Sanders Canyon and Walker Formations, and by the 'ragged' transition from volcanics to Quaternary sediments along the northern flank. This 'ragged' transition is caused by erosion-resistant dikes upholding north-trending ridges that extend well away from the mountain front into the Quaternary basin to the north. A fault contact, in contrast, would have a sharp, well-defined transition from bedrock to Quaternary.

We recognized and mapped seven pre-historic uppermost Tertiary and Quaternary deposits. Divisions were based upon 1) relative soil development (Figure 7), 2) sediment characteristics, 3) allostratigraphy, and 4) the presence of shallow bedrock. The oldest deposits (Tsf and QTa) bear strongly developed and strongly cemented (Stage III+-IV or greater) carbonate horizons and overlie relatively shallow bedrock. QTa deposits are also associated with the highest and most degraded surfaces preserved near the Church Mountain highlands. The middle two deposits (Qao1, Qao2) bear strongly developed but not as cemented (Stage III-III+) carbonate horizons, generally overlie unexposed bedrock, and underlie relatively high surfaces. Qai bears moderately developed (Stage I+ to weak III) carbonate horizons, strong clay illuviation textures, and reddened colors. D.J. Koning obtained radiocarbon ages on charcoal from equivalent deposits on nearby quadrangles of 14.1, 20.3, and 22.6 ka. Qay1 bears weakly to moderately developed (Stage I to II+) carbonate horizons, local evidence of clay illuviation, and brown colors. Koning obtained a radiocarbon age of 8.17±0.05 ka for this deposit on a neighboring quadrangle. These last two deposits are relatively restricted in their extents, suggesting only local backfilling during these periods. Qay2 bears no to weak carbonate accumulation (up to Stage I+), no evidence of clay illuvation, and brownish gray colors. It most commonly fills swales carved into older deposits, where slopewash has accumulated, but is also found as terraces along the larger streams.

The historic period is generally marked by deep gullies developed in valley alluvium, but well bedded pebbles seem to record local accumulation of gravels along streams, and gully mouth fans are depositing local thin alluvium (Qahgf) throughout the basin on the north side of the Church Mountain highlands.

Figure 7 - Gully cut exposes some of the soil characteristics used to differentiate units. Gray unit with white carbonate patches at base is Qao; medial, thin, brown deposit is Qay1; brownish gray uppermost deposit is Qay2. For scale, Qay2 is ~1.25 m thick.

STRUCTURE

The Church Mountain highlands are cut by numerous faults of a variety of attitudes. Only a few faults were found exposed, but all of these dipped in the direction of the down-thrown block, suggesting all faults in the area are normal faults. Northwest trends are dominant on the west flank of the highlands, while northeast trends are common to the interior of the highlands. The timing of faulting is not well constrained, but at least one fault appears to end at the margin of the monzodiorite of Pine Canyon, suggesting the fault is older than the intrusion; it is, however, a poorly exposed area, and, depending on the attitude of the contact and the slip direction of the fault, offset could easily be masked by a small apparent offset of the map pattern. Given that the faults appear to be extensional (normal), the most likely causes of faulting are 1) regional extension associated with the Rio Grande rift and 2) local extension associated with magmatic intrusion, such as due to doming over intrusive bodies or collapse along intrusion margins. Differentiating between the two likely causes is beyond the scope of this study.

Bedding attitudes and contact map patterns indicate that bedding is mostly moderately (15-20°) east-dipping across the western two-thirds of the map area, but largely horizontal to slightly south-dipping along the north flank of the highlands in the eastern third; the attitudes of bedding in the central highlands in the eastern third is not well constrained due to numerous intrusions, poor exposure, and inferred significant paleotopography. This is consistent with the location of the map area on the western limb and near the center of the synclinal Sierra Blanca basin (Kelley and Thompson, 1964; Weber, 1964).

ECONOMIC GEOLOGY

Parts of the Church Mountain quadrangle lie within the Willow Hill, Schelerville (or west Bonito), and Nogal mining districts. Numerous exploration pits and adits pepper the highlands of the quadrangle, most of which were examined and analyzed by Griswold (1959), Griswold and Missaghi (1964), and/or Segerstrom et al. (1979), and the reader is referred to these publications for more detail on the economic prospects of the area. Below is simply a quick summary of these authors' results.

The first known mining activities in the area date back to the 1860's with placer mining below Dry Gulch to the west of the Church Mountain quadrangle (Griswold, 1959). Mining and prospecting continued on the quadrangle intermittently for the following century, with the last known significant development circa 1956-57 with the New Mexico Copper Corp. developing properties in Water Canyon, only to abandon the area when copper prices fell, and the then-Climax Molybdenum Co. exploring the Rialto stock near the junction of Indian and Nogal Creeks (Griswold, 1959). We do not know of any significant exploration or attempts at mining on the quadrangle since then.

Segerstrom et al. (1979) performed a thorough reconnaissance-level geochemical survey of the exploration pits and adits in the area as a part of a resource evaluation of the White Mountain Wilderness, on which most of the Church Mountain highlands lay. They believed the possibility existed for a low grade molybdenum-copper deposit in the area of the Rialto stock. In fact, Griswold and Missaghi (1964) located a small “known molybdenite-bearing zone” northeast of the junction of Nogal and Indian Creeks on the Church Mountain quadrangle. Despite this potential, and the exploration efforts of the Climax Molybdenum Co., the quadrangle does not appear to have been exploited for molybdenum.

Segerstrom et al. (1979) and Griswold (1959) also examined the numerous adits and pits found along the flanks of the Church Mountain highlands on the Schelerville district. Exploration appears to have chased fissure veins associated with dikes of all compositions, with variable copper, lead, zinc, silver, and gold mineralization. We examined many of these pits in passing, and can attest to the presence of very rare copper mineralization in some of the pits and adits (Figure 8). Despite exploration as early as 1880, and some promising assays by Segerstrom et al., particularly along the western flank of the Church Mountain highlands, the area has apparently only yielded a small volume of production, with most adits not shipping any ore (Griswold, 1959; Segerstrom et al., 1979).

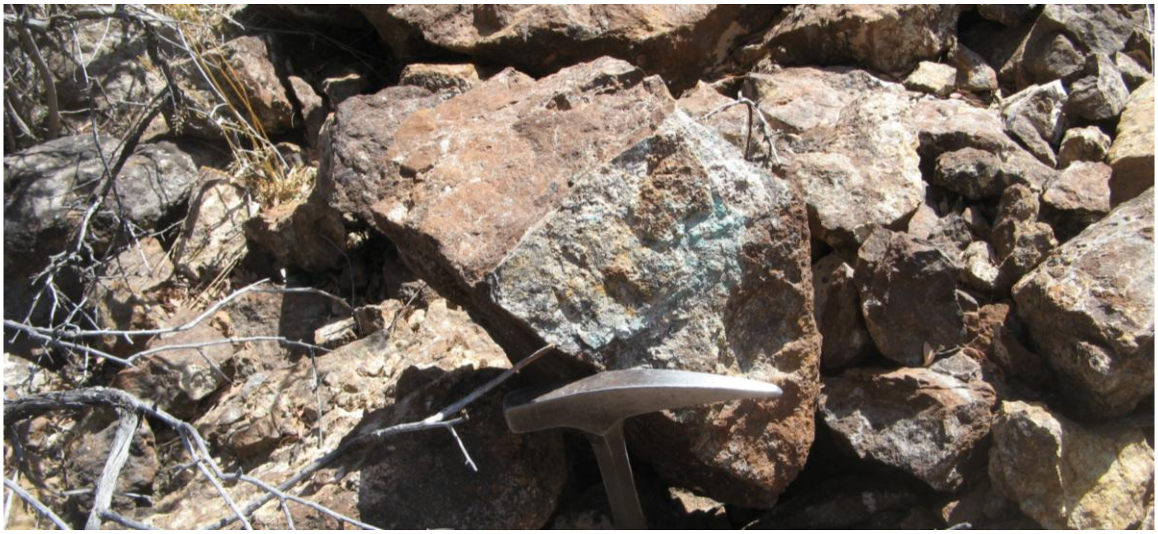

Figure 8 - Local copper mineralization, found in the dump pile near a short adit.

HYDROLOGY

One of the main motivations for this study was to support the NMBGMR’s hydrogeologic studies of the Tularosa basin and surrounding areas. The project is on-going, and the interested reader is encouraged to visit the program’s website for more information on the study (http://geoinfo.nmt.edu/resources/water/home.html). This mapping project did not conduct thorough chemical or hydrologic observations of the area, but did examine the presence and possible geologic controls on springs, the bedrock/basin sediment interface for possibly relevant controls on recharge, and the Quaternary sediments for possible controls on flow through the basin.

Springs

Although several springs are located on the Church Mountain quadrangle, most were either not flowing or were intermittently flowing during the time of the study. Flowing springs were generally confined to the interior of the highlands (Tortolita spring, Gaylord and Hatfield springs, Kountz Canyon spring), while the springs along the highland flanks were not flowing. This could be in part because the interior of the highland was mapped during the fall, following the summer monsoon season, while the northern and northwestern flanks were mapped during the spring, following a dry winter. Regardless, we found no evidence for structural control for all but one spring throughout the study area; the one exception is an unmapped spring near a hill with a given elevation of 6812 ft at the north end of Schelerville Ridge. This developed spring lay at the shoulder immediately south of the hill, and hence has little for a surficial catchment area, yet still had steady flow in both the fall and spring of the 2010-11 season. We can only explain this observation by invoking some sort of fracture flow feeding the spring, although no significant faults exist in the area. We feel that, in general, the dominant controls on spring location are stratigraphic, the topography of the bedrock/Quaternary contact, and catchment area.

During our mapping, we noticed that small springs along drainages often develop at the contact between flow (above) and flow breccia (below), particularly in our unit of Barber Ridge. Flow paths possibly develop along these contacts because of a contrast in effective permeability. The solid flow cores appear to develop discrete fractures that can carry water effectively, while the flow breccias develop more diffuse fractures that are not as effective. In addition, there is plenty of fine material in the breccia and conglomerate matrixes that could clog fracture flow paths. Thus the flow cores are possibly effectively more permeable than the breccias. We feel that similar flow paths could develop along the walls of dikes and intrusions, but have not been able to observe this phenomenon.

We also observed intermittent flow down some of the creeks in the highlands, which we attribute to topography of the bedrock/Quaternary contact and increases in catchment area. An example of the later was suggested by the observations of one of us (CTC) while collecting water samples along Tortolita Creek for the hydrogeology group. He noticed that flow in the creek began at Tortolita spring, disappeared about a hundred meters downstream, reappeared at the junction with Norman Canyon, disappeared again, and then reappeared again at the junction with Kountz Canyon. No surface flow was observed in either side canyon near the junction, though a trickle of flow was found up Kountz Canyon a little downstream of the spring there. The dominant control on the location of surface flow in this case appears to be catchment area, which increased sharply at each side canyon junction. This may also be the control on the location of the spring in Goat Canyon, which is located near the collecting point of several first-order drainages (this spring was not flowing when visited), and May spring, located at the junction of Tortolita Canyon and a small side drainage to the north. A combination of catchment area and bedrock/Quaternary contact topography may explain the distribution of springs along Gaylord Canyon, which holds another intermittent creek. When observed in the fall of 2010, flow began at Gaylord spring, disappeared within 50 m, then reappeared at Hatfield spring. The reappearance could be due to shallow bedrock or increasing catchment area.

The spring located north of Little Cub Mountain in Willow Draw is suspected to be caused by shallow bedrock, forcing water flowing through the basin sediments to the surface.

Groundwater recharge from the highlands to basin sediments

A potentially hydrologically significant observation is the ‘ragged’ nature of the contact between the volcanics in the Church Mountain highland and the basin fill along the north flank of the highlands. In this area, several ridges, commonly upheld by dikes, extend north from the main body of volcanics up to ~2.25 km into the basin sediments. In addition, isolated outcrops of volcanic bedrock are found near the bottom of some drainages in the basin sediments. These observations suggest significant relief on the bedrock/sediment contact, and the possible presence of buried ‘canyons’ carved into the bedrock and backfilled. These ‘canyons’ could serve to focus flow coming off the highlands into and through the basin sediments. Relief on the bedrock/basin sediment contact is apparently more subdued over softer Eocene and Mesozoic strata, but hills upheld by thick felsic sills and dikes, such as Hughes Hill and Little Cub Mountain, suggest that buried relief could still be present.

The ‘ragged’ transition is not observed along the western flank of the highlands, most likely because of the more subdued relief over soft Eocene strata. Despite this, shallow bedrock is observed along drainages in the southeast of the study area. The degree of relief on the bedrock/basin sediment contact in this area was not clear, however.

Flow through basin sediments

Along the north flank of the Church Mountain highlands, enough gully exposure exists to suggest that gravelly paleochannels are found at least as far as 2.5 km from the mountain front in Pleistocene sediments. These paleochannels roughly parallel the current drainages. They are generally not cemented by carbonate, and probably act as conduits for water flow through the basin sediments. How and where they terminate beyond 2.5 km was not observed. However, the stream channels and gullies found at the surface today commonly terminate in small gravelly to sandy gully mouth fans. A similar pattern may have existed in the Pleistocene as well.

Along the western flank of the Church Mountain highlands, outcrop observations suggest gravel channels stretched from the highlands to the west off the quadrangle boundary. In fact, gravels are common to the outcrops of Pleistocene sediment all along at least Harkey draw. Hence groundwater flow along at least the larger channels on the west side of the Church Mountain highlands may be relatively rapid and better connected than on the north side. The dividing line between the two modes is likely around Hughes Draw, given the transition in geomorphic patterns seen about this area.

DESCRIPTION OF MAP UNITS

QUATERNARY UNIT DESCRIPTIONS

(Note: colors presented below are derived from comparison to a standard Munsell Soil Color Chart.)

ARTIFICIAL DEPOSITS

af	**Artifical fill (modern)**. Compacted mud, sand, and gravel composing water tanks and filling old gullies, where stream locations have been moved.
di	**Disturbed areas (modern)**. Locates an area that appears to have been used in a gravel sorting operation, disturbing the sediments, soils, and the nearby stream.

COLLUVIAL DEPOSITS

Qc	**Colluvium (Holocene).** Gravel and sand deposited along steep slopes. Poorly exposed, but generally poorly sorted and unstructured, with weak to absent soil development. Only mapped where potentially or clearly obscuring important geologic relationships. Probably 1-4 m thick.
Qtal	**Talus (Holocene).** Gravels deposited along steep slopes with little to no matrix material. Poorly sorted angular pebbles to local boulders of **Tcp** that generally lack vegetation and often are visible on aerial imagery. Clasts are often derived from upslope cliffs of **Tcp**. Probably 1-4 m thick.
Qls	**Landslides (Holocene).** Deposits of large, (semi)cohesive blocks derived from uphill escarpments of competent rock. Exposure is rare, but deposits are probably 1-6 m thick.

TERRACES OF TORTOLITA CANYON

Sandy gravel that underlies terrace landforms was subdivided according to terrace surface height above modern stream grade. No exposures were observed, but terrace risers (sides) contain abundant cobbles and boulders.

Qtt2	**Younger terrace sediment of Tortolita Canyon (upper Pleistocene).** Surface is 4-5 m above modern stream grade.

Qtt1	**Older terrace of Tortolita Canyon (lower to upper Pleistocene).** Surface is 5-8 m above modern stream grade.

ALLUVIAL FANS OF TORTOLITA CANYON

Sandy gravel that compose alluvial fans. No exposures were observed, but terrace risers (sides) contain abundant cobbles and boulders.

Qfty	**Younger alluvial fan sediment (Holocene).** Very fine to very coarse sand with minor (1-10% estimate) silt and clay. Sand is a grayish brown color. Gravel is mostly pebbles and cobbles, with minor boulders. No notable soil development. 2-4 m-thick.
Qfto2	**Intermediate alluvial fan sediment (Pleistocene).** Alluvial fan whose surface grades into terrace unit Qtt1.
Qfto1	**Older alluvial fan sediment (Pleistocene).** Alluvial fan whose surface appears to be geomorphically above that of terrace unit Qtt1.

ALLUVIAL DEPOSITS

Qca	**Alluvium and colluvium, undifferentiated (middle? Pleistocene to Holocene).** Alluvial and colluvial gravels along streams within the highlands, undifferentiated. Exposures along major streams within the Church Mountain highlands show that **Qao**-, **Qay1**-, and **Qay2**-equivalent deposits are preserved all along these streams, but their extents are not mappable at this scale except locally. They are thus mapped together and along with surrounding colluvium. 0 to 6 m thick.
Qah	**Historic alluvium (0-150? years old).** Gravel to locally sand deposited by historic discharge events along the larger streams in the area. Deposits are well bedded and lack notable soil development, and are generally inset below the top of nearby Qay deposits though locally the tops roughly coincide. Deposits vary from very poorly to moderately sorted and locally bouldery to fine pebbly downstream. Clasts are generally subangular to subrounded, with lithologies reflecting upstream exposed bedrock (dominantly Tertiary volcanics and instrusives). 1 to 3+ m thick.
Qahgf	**Historic gully-mouth fan alluvium (Historic).** Interfingering gravel and sand deposits in distributary fans at the mouths of active gullies. Gravels are matrix-poor, poorly to very poorly sorted pebbles and cobbles in bars that fine away from the gully mouth. Sands are poorly sorted and typically dominate swales and the downstream ends of the fans. Bar and swale topography is common and vegetation is typically sparser than on

	surrounding deposits. No soil development is apparent. Probably <1 to 2 m thick.
Qay2	**Younger alluvium, younger subunit (middle to upper Holocene).** Brownish-gray sand and gravelly sand with local pebble interbeds. Sand is typically poorly sorted and medium- to fine-grained, though overall sand sizes range from very fine to very coarse, and found in weakly bedded to massive deposits. Rare (<1-2%) fine pebbles are scattered throughout the sands, and found as thin discontinuous lenses and in rare channels. Channels, generally at the base of the deposit and apparently only close to the mountain front, can be well bedded and gravel-rich with rare (<2%). Soil development is weak, with invisible to Stage I carbonate accumulation, typically brownish gray colors (10YR 3/2 to 7.5YR 5/3), and local Stage I (filaments) gypsum accumulation. **Qay2** sands are locally capped by thin **Qah** alluvium. The base of **Qay2** is typically wavy but planar, with local channels incising up to 2 m into underlying **Qay1** deposits. 0.5 to 2 m thick, locally up to 4 m thick where the base is channelized.
Qay2h	**Younger alluvium, younger subunit, and historic alluvium, undifferentiated (middle Holocene to Recent).** Units **Qay2** and **Qah**, undifferentiated. See individual descriptions for more information. Used where the two units cannot be separated due to the scale of mapping. 1 to 4 m thick.
Qay1	**Younger alluvium, older subunit (lower Holocene).** Brown pebbles and sands with rare cobbles. Gravels dominate closer to the mountain front, occupying up to 80% of the deposit with up to 20% cobbles at ~1 km from the mountain front, but fining to be 5-30% of the deposit with <1% cobbles further away. Along the western flank of the Church Mountain highlands, continuous gravel beds apparently persist across the quadrangle and gravels are more common. On the north flank, gravel beds decrease in abundance rapidly away from the highlands, apparently being restricted to rare channels and discontinuous lenses by ~2.5-3 km away from the mountain front. Gravels persist as isolated matrix-supported clasts throughout the quadrangle, however. Sands are poorly sorted and fine- to coarse-grained. Deposits typically fine up-section and are well-bedded to massive, with structure generally being best in gravel-rich channels and worst in sand deposits. Soil development is weak to moderate, with Stage I to II+ carbonate accumulation, weak clay illuviation textures, and locally abundant Stage I gypsum accumulation. Colors range from local reddish brown 5YR 5/2 to more common 7.5YR 4/2 to 6/3 browns. The base of the deposit is commonly erosive and wavy and locally channelized into underlying **Qai** or **Qao**. Charcoal from the neighboring Godrey Peak quadrangle yielded a radiocarbon age for this deposit of 8.17 ±0.05 kyr. BP. Deposit is 1 to 4 m thick.

Qay	**Younger alluvium, undifferentiated (Holocene).** Units **Qay2** and **Qay1** undifferentiated. See individual descriptions for more information. Used where the two units cannot be separated due to the scale used or due to the lack of a surficial expression of their individual distributions. 0.5 to 4 m thick.
Qayh	**Younger alluvium and historic alluvium, undifferentiated (Holocene to Recent).** Units **Qay** and **Qah**, undifferentiated, see individual descriptions for more information. Used where the two units cannot be separated due to the scale of mapping. 1 to 4 m thick.
Qai	**Intermediate-aged alluvium (uppermost Pleistocene).** Reddish-brown, often clay-rich sands and pebbly sands with local gravel interbeds. Deposits are typically massive pebbly sands with pebbles as isolated matrix-supported clasts and thin discontinuous lenses. Gravel beds are common directly adjacent to the mountain front, where clasts can be up to 20 cm diameter and beds are continuous, well-bedded, and clast-supported but matrix-rich. Gravel channels, with up to 10% cobbles, are also locally present in **Qai** deposits at least 1-1.5 km away from the mountain front. Soil development is moderately strong, with common Stage I-II+ carbonate accumulation, common to abundant Stage I gypsum accumulation, common clay illuviation with macroscopic illuvial textures, reddish brown colors (5YR 4/3 to 5YR 6/3), and rare disintegrating clasts. The base of the deposit is commonly planar. The deposit is only locally present between deposits of **Qao** and **Qay1**, and only rarely found at the surface. Carbon from similar deposits on neighboring quadrangles yielded radiocarbon ages of 14.1, 20.3, and 22.6 ka. 0 to 2 m thick.
Qao	**Older alluvium, undifferentiated (Pleistocene).** Gravel and sand deposits characterized by strongly developed carbonate horizons, buried soils, and relatively coarse gravel sizes. Generally assigned to either **Qao2** or **Qao1** based on the relative height of the surface capping each deposit, but these divisions are entirely allostratigraphic and not based on sediment characteristics. Gravels are poorly to moderately sorted pebbles to cobbles and local boulders, generally in clast-supported and well-bedded and commonly cross-bedded deposits, although strong soil development can destroy structure and lead to matrix support. Boulders as large as 1.25 m across are found adjacent to the mountain front, but over most of the quadrangle the maximum clast size is 30 cm diameter. Sand deposits are generally massive and pebbly and contain broad channels of gravels. Relative proportions of sand and gravel as well as gravel sizes vary considerably across the quadrangle, but in general the deposits grade from pebble and cobble dominated within 1-2 km of the mountain front to interfingering and intercalated pebble-dominated and sand-dominated deposits further away. To the west of the Church Mountain highlands, this

	persists west to the quadrangle boundary; to the north of the Church Mountain highlands, exposure is poor but suggests that the deposits transition to sand-dominated at around 3-4 km from the mountain front. Weakly to very strongly developed buried and exhumed soils are common to **Qao** deposits; some are characterized by simple reddening, but the strongest soils have Stage III+ (possibly degraded Stage IV) carbonate horizons, local Stage I gypsum accumulation, local clay-rich textures, rare disintegrating clasts, and colors from 2.5YR 4/3 to 5YR 6/3 (colors for sediment without visible carbonate). Deposits are commonly capped by a thin (less than 0.5 m thick) soft bioturbated zone that consists of gravels from underlying **Qao** deposits mixed with light brownish gray slopewash; these gravels often have thick coats of carbonate where overlying Stage III carbonate horizons. Thickness of **Qao** deposits is poorly constrained due to poor exposure of the basal contact, but **Qao** is 1 to at least 10 m thick.
Qao2	**Older alluvium, younger subunit (upper? Pleistocene).** Gravel and sand characterized by strongly developed carbonate horizons and buried soils capped by a surface inset upon that of **Qao1**. See description of **Qao** for a description of this unit's sediments. As no sedimentary difference could be established between deposits of **Qao1** and **Qao2**, these deposits could be the same with the lower surface being entirely erosional. This problem precludes confidently determining the deposit's thickness, but it is probably 1 to 3 m thick.
Qao1	**Older alluvium, older subunit (middle? to upper Pleistocene).** Gravel and sand characterized by strongly developed carbonate horizons and buried soils capped by a surface inset upon by **Qao2**. See description of **Qao** for a description of this unit's sediments. As no sedimentary difference could be established between deposits of **Qao1** and **Qao2**, these deposits could be the same with the lower surface being entirely erosional. Thickness is difficult to determine as the basal contact is often poorly exposed, but **Qao1** is 1 to at least 10 m thick.
QTa	**High-level alluvium (upper Pliocene? to lower Pleistocene).** Coarse gravels characterized by very strongly developed carbonate horizons and relatively shallow bedrock. Exposures are rare, and the unit is commonly mapped by allostratigraphy, as it underlies the highest and most dissected alluvial surfaces on the quadrangle. Gravels are typically coarser even than those of **Qao**; boulders as coarse as 1 m diameter are found on **QTa** surface tops as far as 1.25 km from the mountain front. Locally exposed carbonate horizons are up to 3 meters thick and typically strongly cemented by carbonate; although laminar tops are not preserved these horizons are likely Stage IV or greater in development. Where overlying volcanic or indurated Mesozoic rocks, bedrock is commonly exposed at the base of these deposits; where overlying softer Eocene rocks (**Tsc**, **Tcm**), bedrock exposures are rare. Basal sediments, just above bedrock,

are commonly heavily cemented by carbonate. Deposits are 1 to at least 35 m thick.

Tsf **Fine-grained Santa Fe Group(?) deposits (Pliocene?).** Clayey very fine- to fine-grained sand that is vaguely laminated to massive. Sand is partly derived from the Sanders Canyon Formation. Well consolidated. 1-5 m thick.

TERTIARY VOLCANIC DEPOSITS

SIERRA BLANCA VOLCANICS

Tcp **Church Mountain phonolite (Oligocene).** Light gray to dark gray, weathering to beige, buff, and reddish orange, crystal-rich flows with variable lithic content, sparse pumice, and variable foliation. Phenocrysts are dominantly medium to coarse grained potassium feldspar and plagioclase feldspar, with local sparse to common fine to medium grained biotite and amphibole. Lithics are generally pebble sized and sparse to absent, but locally constitute up to 10% of outcrops. Pumice is sparse to absent, fine pebble in size, and flattened. Foliation varies from absent to strong, but foliation planes are rarely extensive, and the flattening is generally most visible in the attitudes of lithics and plagioclase lathes, which weather high on weathered surfaces. Foliation attitudes are highly variable but seem to indicate a dominantly moderate (15-25°) eastward dip. Flows are often cliff formers, and locally form prominent bluffs that shed talus to bury underlying units. Individual flows have from 1 to 10 meters of exposed thickness. Flows have variable magnetic properties, from strongly deflecting a compass to having no effect. Generally, deflection is more common in the upper flows of **Tcp**. Included in this unit are interbedded volcaniclastic sediments and fine grained lava flows which form slopes between **Tcp** flows and are very locally exposed in saddles, and a few vitrophyric flows that grade upward and laterally into dark gray **Tcp**. A sample of a **Tcp** flow, CMC-83 (Table 1), was geochemically analyzed and is the basis for the use of the term ‘phonolite’ (Figure 2a). Weber (1964) suggested the range of properties in the Church Mountain phonolite are consistent with a thick lava dome with interbedded flows, tuffs, and volcaniclastics. The basal contact is consistently obscured by colluvium, even where it can be accurately constrained, but outcrop patterns suggest an irregular contact probably influenced by paleotopography. Traverses up poorly-exposed ridges on the north flank of Church Mountain also suggest up to 85 m of interbedded **Tcp** and **Twdf** flows lay at the base of **Tcp**; the contact was placed at the point where **Tcp** appears to dominate, which coincides with where bold cliffs of **Tcp** begin to appear. A whole rock K-Ar age of 31.8 ± 1.3 Ma was obtained on a vitrophyre from SW ¼, NE ¼, Sec. 2 T9S R11E, circa 33°33’27”N, 105°46’08”W (Weber, 1971). Up to ~500 m thick around Church Mountain.

Tnt	**Nogal Peak trachyte (Oligocene).** White to pale pinkish gray, slightly porphyritic to aphyric trachyte lavas with intercalated flow and flow breccia. Flows contain phenocrysts of plagioclase, biotite, and hornblende in a trachytic matrix of fine plagioclase, clinopyroxene, biotite, hornblende, sparse sanidine and devitrified glass (Goff et al., 2011). 25 m thick.
Tkcf	**Lava flow of Kountz Canyon (Oligocene).** Crystal-rich (15-20%) porphyritic flows with distinctive zoned, blocky to elongated feldspar phenocrysts that are dark gray at the center and white on the rim. The feldspar phenocrysts are <4-7 mm across. Other phenocrysts include green pyroxene (< 2mm). This flow was deposited on a rugged paleotopography. Top is locally vesicular. A possible vent is located on the divide between the heads of Norman and Kountz canyons. Up to 25 m thick.
Tgpfl/Tgpfu	**Lava flows of Gaylord Peak (Oligocene).** The upper flow (**Tgpfu**) is a porphyritic lava (15-20% phenocrysts) with a vesicular top and an aphanitic pink to gray matrix. Phenocrysts are potassium feldspar and green pyroxene; the pyroxene commonly forms in clusters. The feldspar phenocrysts have a bimodal range of grain sizes. The larger crystals are 6-7 mm across and are equant. The smaller (<2 mm) phenocrysts are more elongate. The lower flow (**Tgpfl**) is a porphyritic lava (5- 10% phenocrysts) containing potassium feldspar and pyroxene in an aphanitic to fine-grained gray to pink matrix. The phenocrysts are < 4 mm across. Maximum thickness of the upper flow is 150 m; the lower flow is <50 m thick.
Tptf	**Lava flow, Pennsylvania trail (Oligocene).** Aphanitic to sparsely porphyritic (<2% crystals) lava capping a hill with a spot elevation of 8594 along the Pennsylvania trail. The flow is more porphyritic upsection and contains potassium feldspar and pyroxene crystals <2-3 mm across. About 60 m thick.

WALKER VOLCANIC BRECCIA

(Formerly the Walker Andesite Breccia of Thompson, 1972, 1973)

Twd	**Unit of Double Diamond Peaks, undivided (Oligocene).** Intercalated plagioclase-phyric porphyry lavas, plagioclase- and amphibole-phyric porphyry lavas, and pebble to locally boulder conglomerates. Typically assigned to either **Twdf** or **Twds** depending on whether flows or sediments dominate, respectively; flows and conglomerates are described

in more detail under those headings, below. Mapped as **Twd** where poor exposure and/or thorough interbedding of flows and conglomerates precludes dividing the two into separate map units; this is mainly in the area of Diamond Peak, where significant alteration, demonstrated by a high degree of bleaching and oxide staining, has weakened the bedrock and resulted in very poor exposure. Up to ~280 m thick, in the area of Diamond Peak.

Twdf **Unit of Double Diamond Peaks, flow-dominated subunit (Oligocene).** Plagioclase porphyry lava flows of variable texture, color, and phenocryst mineralogy. In the interior and southwestern portions of the Church Mountain highlands, this unit consists primarily of plagioclase-phyric flows with no other phenocrysts; along the ridge between Diamond Peak and Church Mountain and further north onto the Double Diamond Peaks, these intercalate with common plagioclase/amphibole porphyries, and locally along Shelerville Ridge the plagioclase porphyries intercalate with pyroxene/plagioclase porphyries. Colors for plagioclase-phyric flows vary from light purplish gray to bluish gray to beige (where bleached) to reddish or orangish brown (where bleached and oxide-stained); for plagioclase- and amphibole-phyric flows, colors range from brownish gray to reddish gray to dark beige, and these flows are generally not bleached or oxide stained. Textures commonly range from sparse (~1%), fine grained (<1 mm across) phenocrysts to common (up to ~20%), medium grained (up to 5 mm across) crystals. Flow foliation is generally absent but locally well developed. Lithics are rare but locally present and abundant. Individual flows are poorly exposed and not laterally traceable, but up to 10 m thick. The basal contact appears conformable and planar along the outside of the Church Mountain highlands; contacts within the highlands themselves seem to be heavily influenced by paleotopography, however, with some contacts darting across topography, with apparent near-vertical attitudes. Geochemistry indicates there is a variety of chemistries for these lavas; a sample of plagioclase-phyric lava plotted as a phonotephrite (sample CMC-139, Table 1, Figure 2a), while a sample of plagioclase- and amphibole-phyric lava plotted as basaltic trachyandesite (sample CMC-138). Lavas contain local interbeds of volcaniclastic sediments as described below under **Twds**. Cross-section A-A’ indicates the unit is at least 160 m thick in the Double Diamond Peaks area, while map patterns suggest the unit is as much as 200 m thick below Church Mountain and up to 280 m thick around Diamond Peak.

Twds **Unit of Double Diamond Peaks, sediment-dominated subunit (Oligocene).** Purplish gray to gray to beige (where bleached) and orangish brown (where oxide-stained) pebble to cobble to locally bouldery volcaniclastic conglomerates. Clasts are subrounded to angular, generally clast-supported, and poorly to very poorly sorted. Their lithologies reflect local sources, dominantly plagioclase porphyries of various textures, including ‘turkey track’ coarse plagioclase phenocrysts. Unit is generally very poorly exposed. The basal contact appears to be generally conformable and planar along the periphery of the mountains, whereas within the mountains paleotopography seems to have strong influence over contact geometry. In the headwaters of the west fork of Pine Canyon, the basal contact rises from west to east along the headslope to pinch the unit out from between **Twas** and **Twdf**. In the headwaters of the south fork of Pine Canyon as well as in Diamond Spring Canyon, bands of volcaniclastic conglomerates dart across topography with apparent steep contacts, possibly indicating the presence of paleocanyons. Irregularly-oriented **Twds**/**Twdf** contacts are also observed in these areas at the outcrop scale, further suggesting paleotopographic influences. Unit contains local interbeds of lavas like those described above under **Twdf**. Cross-section A-A’ indicates the unit is 0-40 m thick in the Double Diamond Peaks area, whereas paleocanyon-filling deposits of **Twds** in the Diamond Peak area may be as much as 140 m thick.

Twas **Tuff of Argentina Springs (Oligocene).** A highly variable unit defined by lithic-rich, plagioclase-phyric, flow-foliated (rheomorphic) ignimbrite intervals. The ignimbrite intervals are black to gray to yellowish tan, slightly welded to densely welded, and lithic-rich, with flattened pumice (fiamme) with a maximum aspect ratio of ≥25:1. Small to medium (up to 5 mm across) abundant phenocrysts consist of sanidine, plagioclase, biotite, opaque oxides, ≤2% quartz and tiny altered hornblende(?) in a banded eutaxitic groundmass (Goff et al., 2011). Lithic fragments consist of white chert to fine-grained sandstone and a variety of light to dark-colored volcanic rocks, including syenitic rocks. In areas of good exposure, particularly along the northern flank of the Church Mountain highlands, there appears to be a volcaniclastic sedimentary interval between two zones of strongly foliated lithic-rich ignimbrite. This interval is clast-supported pebbly to locally bouldery with a fine purplish to bluish gray matrix, locally containing plagioclase xenocrysts. It is possible that this ‘sedimentary’ interval is in fact a very lithic-rich medial zone of ignimbrite, but the lithic-rich nature and clast-supported fabric is more reminiscent of a sedimentary conglomerate than a flow. This medial interval appears to thicken in the interior of the highlands, contributing to the increase in thickness seen in map patterns; poor exposure inhibits separating the volcaniclastic interval from the ignimbrite, however. **Twas** is commonly strongly bleached and oxide stained, altering the natural color to light beige to reddish or orangish brown. The basal contact appears to be conformable and planar where observed along the periphery of the highlands; we suspect that the contact becomes more irregular within the highlands. One or both of the ignimbrite intervals likely correlates to the tuff of Bucky Pasture in the Godfrey Hills to the west. Unit is 40 to 120 m thick.

Twrtau	**Unit of Rattlesnake Canyon, upper (basaltic) trachyandesite subunit (upper Eocene? to Oligocene).** Light purplish gray to medium gray flows with common (3-15%) white plagioclase phenocrysts up to 9 mm across. Flows also locally contain clinopyroxene <3 mm across. These flows do not bear lithics and have only a weak flow foliation. Basal contact generally appears conformable and planar, although the unit appears to locally pinch out in the northwestern corner of the Church Mountain highlands, and appears to fill a paleovalley on a ridge immediately east of the mouth of Goat Canyon. Not present along the western flank of the highlands. 0 to generally ~30 m thick, and up to 90 m thick where apparently filling a paleovalley.
Twrtbu	**Unit of Rattlesnake Canyon, upper trachybasalt subunit (Upper Eocene? to Oligocene).** Light gray aphanitic lava flow located about 10 to 15 m below the tuff of Argentina Springs. Continuous in the south, pinches out to the north, and is absent along the north flank of the Church Mountain highlands. About 6 m thick.
Twrfp	**Unit of Rattlesnake Canyon, fine-grained flow with small pyroxene phenocrysts (upper Eocene? to Oligocene).** Orange-brown to pale orange to pale gray when weathered, dark gray-brown to medium gray on fresh surfaces. 20% phenocrysts of plagioclase and pyroxene, all of which are 1-2 mm in length or less.Phenocrysts equally plagioclase and pyroxene (50-50 mix). Pyroxene occurs as thin needles that, when weathered out, leave the outcrop with a distinct pattern resembling pins or needles scattered across the rock faces. On fresh surfaces, pyroxene is reddish in color, indicating slight alteration. Outcrop locally has platy appearance, otherwise massive. Top of unit vesicular in places. Locally, weathering produces a grainy or "sugary" look to the outcrop. Thickness highly variable.
Twrvs	**Unit of Rattlesnake Canyon, volcaniclastic sedimentary subunit (upper Eocene? to Oligocene).** Dark reddish to purplish gray to medium gray, generally matrix-supported and poorly sorted pebble to cobble conglomerates. Outcrops are generally massive, with clast size variability and local well-indurated zones defining bedding planes. Clast composition reflects local sources, with the dominant lithologies being dark aphyric flows and plagioclase porphyries of varying textures. Unit includes several intercalated lava flows, most of which are aphyric to fine plagioclase-phyric, with common mm- to cm-scale spotting; some of these flows are laterally continuous over kilometers, and locally form prominent bluffs visible on aerial imagery. A sample from one such prominent lava, CMC-141 (Table 1), was geochemically analyzed and classifies as a basaltic trachyandesite (Figure 2a). The thickest interval of this unit is found immediately below **Twrtbu** and **Twrtau**, with a thickness that varies from

~50 to 110 m, thinning to the east. Thinner intervals, ~10 to 20 m thick, are locally found overlying these lavas.

Twrtbl **Unit of Rattlesnake Canyon, lower trachybasalt subunit (upper Eocene? to Oligocene).** Dark gray, fine-grained to aphanitic trachybasalt to trachytic lavas that form conspicuous thin (0 to 20 m tall) shelves. Flows usually contain small phenocrysts of plagioclase, clinopyroxene ± iddingsitized olivine (Goff et al., 2011). Some flows have a spotted texture on weathered surfaces, other flows have a micaceous sheen. Still other flows in this succession have a banded trachytic texture. The lavas are interbedded with volcaniclastic sedimentary rocks like those described under **Twrvs**. Unit pinches out to the north and is absent along the northern flank of the Church Mountain highlands. Up to 75 m thick.

Twrtap **Coarse plagioclase porphyritic trachybasalt to basaltic trachyandesite (upper Eocene? to Oligocene).** Distinctive dark gray to gray porphyritic lavas that contain large (1-2 cm across) plagioclase phenocrysts and plagioclase clots. The elongate plagioclase laths make up 15 to 25% of the rock. Groundmass consists of plagioclase, clinopyroxene, altered olivine, opaque oxides and glass (Goff et al., 2011). 1 to 4 m thick.

Twrtal **Unit of Rattlesnake Canyon, lower (basaltic) trachyandesite subunit (upper Eocene? to Oligocene).** Lumped unit of reddish brown to gray porphyritic lava flows that contain phenocrysts of plagioclase and clinopyroxene. Variably crystal rich to crystal poor (10-25% of rock mass), with plagioclase phenocrysts obvious on weathered surfaces. Most phenocrysts are <5 mm across, but flows with plagioclase phenocrysts up to 10 mm across are common. Aphanitic trachybasalts also occur in this interval. The nature of the basal contact with the underlying plagioclase- and pyroxene-phyric **Twbf** varies from south to north; in the south, it is a sharp contact defined by a thin section of aphyric flows, followed by the pyroxene-aphyric, plagioclase-bearing flows of **Twrtal**. In the north, the contact is more gradational, as the size of the pyroxene phenocrysts gradually decreases upsection and finally disappears; the contact here was placed at the top of the uppermost lava with macroscopically visible pyroxene crystals. Thickness varies considerably across the field area, from a maximum of 290 m on the west flank of the Church Mountain highlands, to a minimum of 35 m in the Pine Canyon area, from where it thickens again to the E to about 145 m thick.

Twbf **Unit of Barber Ridge, lava flow-dominated subunit (Upper Eocene to Oligocene).** Intercalated plagioclase/pyroxene porphyry lava flows and breccias and plagioclase ± pyroxene porphyry flow breccias, with minor volcaniclastic conglomerates. Plagioclase/pyroxene porphyry lavas are medium gray to purplish, reddish, brownish, and greenish gray, with 10-30% phenocrysts of plagioclase and pyroxene most often 1-4 mm across, but with pyroxene crystals commonly up to 1 cm across. Solid flow cores are typically thin (1-3 m thick) but with thick breccia zones up to 6 m thick. Plagioclase porphyry monolithic breccias are commonly bluish gray in color and crystal-rich, 30-50% crystals, and can be up to 20 m thick. Minor volcaniclastic conglomerates are similar to those described under **Twbs**. A sample of plagioclase/pyroxene porphyry, CMC-151 (Table 1), was geochemically analyzed and classifies as an alkali basalt (Figure 2a). Basalt contact appears to be conformable, and is placed at the sharp transition from heterolithic sediment-dominated to flow (breccia)-dominated intervals. Exposed thickness of 140 to 200 m.

Twbs	**Unit of Barber Ridge, conglomerate- and breccia-dominated subunit (upper Eocene to Oligocene).** Coarse volcaniclastic conglomerates and breccias with minor intercalated flows. Medium gray to reddish and purplish gray, generally clast-supported heterolithic conglomerates and breccias of pebbles to cobbles and very local small boulders of plagioclase ± pyroxene porphyries of varying textures. Beds are massive with irregular contacts and are up to 2 m thick. These are intercalated with minor plagioclase/pyroxene porphyry flows similar to those described under **Twbf**. The basal contact is sharp and irregular. Exposed thickness is 40 to 115 m.

TERTIARY AND MESOZOIC SEDIMENTARY ROCKS

EOCENE SEDIMENTARY ROCKS

Tsc	**Sanders Canyon Formation (upper Eocene).** Interbedded maroon to red floodplain deposits and light gray, sandy channel-fills. Interpreted as a fluvial deposit. The average sandstone/mudstone ratio is about 30:70 (Cather, 1991) and decreases upsection. The channel-fills are light gray, fine- to very coarse-grained (mostly fine- to medium-grained), subangular, poorly to well sorted (mostly moderately sorted), and composed of plagioclase, 10-20% quartz, 5-15% microline and orthoclase, and 25-30% volcanic lithics (including 0.5-2% biotite grains). Sandstone petrologic study by Cather (1991) for the Sanders Canyon Formation give ranges of: 31-65% volcanic rock fragments, 8-41% twinned plagioclase, 7-31% quartz (decreasing up-section), 0-7% microline and orthoclase, 0-4% granite and gneiss rock fragments, 0-3% chert, 0-2% metamorphic rock fragments, and 0-2% sandstone rock fragments. Sandstone is in vague, tabular beds up to 30 cm-thick; these beds are commonly internally laminated (planar-horizontal to tangential cross-laminated, foresets up to 25 cm-thick). Mudstone rip-up clasts are locally observed in the sandstone. 1% very fine to very coarse pebbles and lesser cobbles-boulders (maximum boulder size of 32 x 15 cm); clasts are composed of plagioclase-phyric andesite. Floodplain sediment consists of reddish to

	maroon mudstone, siltstone, and very fine- to medium-grained sandstone (mostly very fine- to fine-grained). The fine-grained floodplain sediment is typically laminated (planar-horizontal, cross-laminated, or wavy), but the fine sandstone may be in very thin to thick beds. Sandstone channel-fills are typically well-cemented by carbonate (Cather, 1991). This unit is older than 38 Ma, which is about the maximum age of the Sierra Blanca volcanic field (Moore et al., 1991), and younger than the Eocene-age Cub Mountain Formation. Unit conformably overlies the Cub Mountain Formation. Variable bedding makes thickness measurements uncertain. An estimate of 150 m was made by Cather (1991), but cross-section A-A' allows a maximum thickness of 400 m.
Tscf	**Sanders Canyon Formation, fine-grained subunit (upper Eocene).** Maroon to red floodplain deposits. Locates areas of the Sanders Canyon Formation where the floodplain deposits dominate.
Tcm	**Cub Mountain Formation (lower to middle Eocene).** White to pale yellow to light reddish gray, arkosic channel-fill sandstones interbedded with reddish floodplain deposits of mudstone and very fine- to fine-grained sandstone. Interpreted as a fluvial deposit. The slightly coarser texture of the sand (mostly medium-grained), more “pockety” outcrop appearance, and reddish fine-grained sandstone beds serve to distinguish this unit from the underlying Crevasse Canyon Formation. The unit differs from the overlying Sanders Canyon Formation by lesser amounts of volcanic detritus in its sand fraction (less than 20%). Channel-fill sandstone is mostly pale yellow to pale yellowish orange (10R 8/6), but ranges from white to pale red. Sand is fine- to very coarse-grained (mostly medium-grained), subangular to rounded, and moderately to well-sorted. Sandstone petrologic study by Cather (1991) for the Cub Mountain Formation give ranges of: 50-70% quartz, 3-15% microline and orthoclase, 2-16% granite and gneiss rock fragments, 5-11% volcanic rock fragments, 1-9% chert, 0-9% metamorphic rock fragments, 0.5-6% twinned plagioclase, and 0-3% sandstone rock fragments. Multiple scour surfaces divide beds with low-angle, large-scale, arcuate crossbeds and planar-beds (Lucas et al., 1989). Sandstone is massive to cross-stratified. Channel-fills are locally conglomeratic, with gravel consisting of quartz + quartzite, rhyolite, and chert. Pebbles are 2-10 mm, subrounded, and moderately sorted. There are at least two beds of limestone pebble conglomerate. Sandstone is commonly hematitic and non- to slightly clalcareous. Floodplain sediment consists of grayish red claystone, mudstone, siltstone, and very fine- to fine-grained sandstone; these strata are slightly calcareous. Fossils collected from lower part of unit are interpreted to be Eocene, probably late Wasatchian to earliest Bridgerian (Lucas et al., 1989). Definition of the base of this unit differs from that of Cather (1991). Koning et al. (2011) define the base of the Cub Mountain Formation at the top of the paleosol commonly observed on top of the

Crevasse Canyon Formation. This definition gives a thickness range of 370-570 m.

MESOZOIC SEDIMENTARY ROCKS

Kccu **Crevasse Canyon Formation, upper part (upper Cretaceous).** Intercalated channel-fill sandstones and floodplain deposits. This fluvial sediment differs from the overlying Cub Mountain Formation by its yellowish-greenish floodplain deposits and the slightly finer sand size in channel-fills. About subequal (+/- 20%) sandstone:mudstone strata. Channel-fill sandstone are yellow, fine- to coarse-grained (mostly fine- to medium-grained), subangular to subrounded (mostly subangular), moderately to well sorted, and composed of quartz, 5-15% feldspar, and 3-10% lithic grains (including quartzite or chert) and mafic grains. Sandstone is in thin to thick, tabular beds. Within these beds are common cross-stratification (mostly tangential) or planar-horizontal laminations or very thin beds. Floodplain deposits generally consist of yellow to light gray mudstone, siltstone, and very fine-to fine-grained sandstone in laminated to thin (less commonly, medium), tabular beds. Pebbles are found in channel-fills in the upper part of the unit. Gravel are scattered or in very thin to thick, lenticular to tabular beds. Gravel are rounded, moderately sorted, and composed of rhyolite, felsic intrusive clasts, quartzite, and chert. The pebble-bearing, upper part of this unit probably correlates to the Ash Canyon Member. Top of unit is defined by a 3-4 m-thick paleosol. This paleosol consists of light grayish green, massive sandstone with 10-15% irregular, purplish black (MnO?) concretions. Below the paleosol is 5-10 m of similar sandstone that is not mottled. Locally north of Little Cub Mountain, two similar paleosols were observed that both contained MnO(?) concretions; these were separated stratigraphically by about 10 m. Thickness of 250-270 m (from Koning et al., 2011).

Kccl **Crevasse Canyon Formation, lower part (upper Cretaceous).** Strata similar to that of unit Kccu, but the proportion of floodplain sediment exceeds that of sandstone channel-fills. 1-5% coal beds or organic-rich mudstone in lower part of unit. Thickness of 280-300 m (from Koning et al., 2011).

TERTIARY INTRUSIVE ROCKS

(Note: for the following descriptions, rock names were chosen for geochemical and textural reasons, irrespective of the intrusive nature of the rock; hence, a mafic body with an aphanitic matrix is called a ‘basalt,’ even though the common name for a mafic intrusive is gabbro.)

STOCKS AND MAP-SCALE SILLS

(Units that appear as polygons on the map)

<u>Rialto stock</u>

Tirm	**Monzonite (Oligocene).** This secondary intrusive phase of the Rialto stock consists of gray, weakly porphyritic, fine- to medium-grained monzonite with phenocrysts of plagioclase and small green clinopyroxene in a groundmass of plagioclase, minor potassium feldspar, euhedral biotite, and hornblende. Intrudes the primary Rialto syenite (**Tirs**/**Tirp**) in the Nogal and Indian Springs Canyons. The main phase of the Rialto syenite is pervasively bleached and limonite-stained along the margins of this more mafic stock in Nogal Canyon. Maximum exposed thickness about 60 m.
Tirfw	**Fine-grained white syenite (Oligocene).** This phase of the Rialto stock is generally white and has a fine-grained, equigranular or sugary texture. Potassium-feldspar and trace quartz are discernible with a hand lens; the mafic minerals are altered. The contact between this phase and the main phase of the Rialto stock is gradational. Maximum exposed thickness about 120 m.
Tirs/Tirp	**Syenite to syenite porphyry (Oligocene).** Primary intrusion of theRialto stock. Greenish gray, medium- to coarse-grained syenite containing plagioclase and potassium feldspar, with mafic minerals consisting of clinopyroxene, hornblende and biotite. The center of the stock tends to be slightly porphyritic (**Tirp**), with slightly larger (4-7 mm across) potassium feldspar phenocrysts. Alteration is generally intense near margins of the stock, and consists of epidote and tremolite-actinolite mineralization and Fe-oxide staining. Thompson (1973) reported a K-Ar date on hornblende of 31.4 ± 1.3 Ma. Maximum exposed thickness is 250 m.
Tirtc	**Syenite porphyry of Tortolita Canyon (Oligocene).** Distinctive phase of the Rialto stock characterized by 1-2 cm long elongate and embayed potassium feldspar phenocrysts. Matrix is medium-grained and contains potassium feldspar, hornblende, and trace biotite. This unit is intruded by the main syenite phase of the Rialto stock. Maximum exposed thickness is 100 m.

Blocks of the syenite porphyry of Tortolita Canyon (intrusive with large potassium-feldspar phenocrysts) within the main phase of the Rialto stock. Photograph taken looking east; north is to the left.

Tirfg **Fine-grained gray syenite (Oligocene).** This phase of the Rialto stock is located south of Tortolita Canyon. This phase is sparsely porphyritic with a dark gray fine-grained matrix. This unit contains phenocrysts of green amazonite, pink orthoclase, pyroxene, and biotite. This phase is clearly intruded by the main phase of the Rialto stock and may be intruded by the syenite porphyry of Tortolita Canyon. Maximum exposed thickness is 50 m.

The gray rock is the fine-grained gray syenite with amazonite (**Tirfg**) intruded by the reddish main phase of the Rialto stock. Photograph taken at 429180 3710041 looking west; north is to the right.

Tirx **Xenolith-rich margins of the Rialto stock (Oligocene).** Angular to subrounded blocks of fine-grained syenite and Walker porphyritic to aphanitic lavas and tuff included within medium- to fine-grained Rialto syenite to syenite porphyry near the margins of the Rialto stock. Up to 15 m thick.

Miscellaneous sills

Titlc **Trachyte sill of Little Cub Mountain (Oligocene).** Grains are 0.1-0.8 mm and composed predominately of feldspar. There are 3-8% unidentified mafic grains (possibly amphibole) 0.5-2 mm long. Rock has up to 10% cavities up to 7 mm long that do not seem to be connected or aligned. Rock weathers to a brown color. Maximum thickness of 100 m.

Tihss **Syenitic sill of Hughes Hill (Oligocene).** Light gray to beigish gray porphyritic syenite. Phenocrysts consist of potassium feldspar (5-10%, 1 to 8 mm across, gray to white to pink, largest crystals are zoned), plagioclase (2-3%, up to 1 mm across, clear to white), hornblende (~1%, up to 1 mm across, black to dark green), and possible biotite (<<1%, occurs as platy black ‘coats’ on other crystals and pores). The matrix is granular and appears to be dominantly pink potassium feldspars and hornblende. The sill is moderately foliated, with planes defined by well-aligned crystals. The sill is about 20 m thick at the crest of Hughes Hill, and thins in either direction to about 2 m thick before disappearing under the Quaternary.

Mafic-intermediate intrusions

Tidsb_ **Alkali basalt porphyry of Diamond Spring (Oligocene).** Two isolated bodies of coarse plagioclase porphyry are combined under this designation, a southwestern, coarser intrusion (**Tidsb1**) and a northeastern, finer body (**Tidsb2**). Both bodies are purplish gray to dark gray to locally beige in color. The coarser **Tidsb1** has common (up to ~35% of fresh surfaces) rounded plagioclase lathes 1 to 2 cm long. These are often strongly aligned, but alignments are chaotic and fabrics can be mutually perpendicular within the same outcrop. The **Tidsb1** body trends NNE, with apparent subvertical contacts. Its exposed extent thickens to the NNE, but the poor exposure in Diamond Spring Canyon masks its northern terminus. The finer body, **Tidsb2**, has common plagioclase lathes and blocks from 1 mm across up to 2 cm long. It appears to fine to the north and east. Contacts are poorly exposed, and, unlike **Tidsb1**, are apparently not vertical everywhere. Double Diamond member lavas found along the ridge joining Diamond Peak and the Double Diamond Peaks appear to form a roof over the body, which is found in the head slopes on either side of the ridge. A sample of **Tidsb2**, CMC-140 (Table 1), was geochemically analyzed and classifies as an alkali gabbro (Figure 2b); we choose to use the term ‘basalt,’ however, due to the rock’s aphanitic matrix. No dikes or faults were observed cutting either **Tidsb** body, but both can be seen to intrude strata as young as lowermost **Twdf**.

Tiwb **Alkali basalt porphyry of Wind Canyon (Oligocene).** Medium to dark gray, coarse plagioclase ± fine pyroxene porphyry stock at the mouth of Wind Canyon. Coarse (9 to 20 mm across) plagioclase phenocrysts occupy ~5-10% of the rock, occurring as aligned rounded clear to white lathes. Pyroxene phenocrysts, where present, occur as black blocks up to 3 mm across, occupying ~ 1-2% of the rock. The matrix is moderately granular, consisting primarily of fine plagioclase lathes with lesser pyroxene and other ferromags. The unit was not geochemically analyzed, but its mineralogy is more mafic than that of **Tidsb**, suggesting that this intrusion is also gabbroic. Unit is cut by numerous dikes; it intrudes strata at least as young as **Twrtal**.

Tibu **Basaltic porphyry instrusions, undivided (Oligocene).** Medium to dark gray, coarse plagioclase ± fine pyroxene porphyries found along the poorly exposed northern flank of the Church Mountain highlands and interpreted to be intrusions. These rocks have similar minerologies and textures to those of **Tiwb** and **Tidsb**, suggesting these rocks are also mafic intrusives. Contacts are not well enough exposed to confirm this interpretation, however. Units are intruded by some dikes; stocks appear to intrude **Twb** and lowermost **Twrtal**.

Tipm **Monzodiorite of Pine Canyon (Oligocene).** A light gray to medium gray weathering beige to light brown, fine- to medium-grained phaneritic potassium feldspar-, plagioclase-, amphibole-, and biotite-bearing elongate intrusive plug and associated sills. All minerals are <1 to 2 mm across, with potassium feldspar dominating, plagioclase being second most abundant (up to 30% of fresh surfaces), then amphibole (up to 15%) and biotite (up to ~5%). Generally these crystals appear fresh and undegraded. Rare ‘clots’ of coarser crystals were found at one locality, with plagioclase and biotite crystals up to 4 mm across. The origin of these clots is not known and may be secondary. Outcrops appear massive but may have a very weak foliation defined by aligned amphibole lathes. Contacts are discordant with surrounding strata and appear to be near vertical, with the notable exception of the western margin of the body which ends in a series of sills that pinch out to the west, as seen in the southeastern slope of the Double Diamond Peaks. A sample of **Tipm**, CMC-137 (Table 1), was geochemically analyzed and classifies as a monzodiorite (Figure 2b). The body as a whole is elongate in the east-west direction, and appears to have a broad, low-amplitude, sinusoidal trend. The stock is clearly cut by several dikes. Its relationship to area faulting is not certain, but it appears the Pine Canyon fault does not offset the body. The body clearly cuts strata as young as **Twdf**.

DIKES AND THIN SILLS

(Units that appear only as lines on the map)

Felsic dikes and sills

Tit	**Fine-grained to aphyric trachyte dikes (Oligocene).** White to light gray dikes with aphanitic matrixes and sparse, fine-grained potassium and plagioclase feldspar phenocrysts. Feldspars are clear to white and up to 1 mm across. Dike matrixes are milky and smooth-looking, and often well foliated and crenulated. These dikes are generally thin, up to 1 m across.
Tis	**Medium-grained syenite dikes (Oligocene).** Pink, medium-grained, equigranular dikes and sills composed of potassium feldspar, green pyroxene, occasional biotite and sparse quartz. Dikes may be up to 20 m across; ages of dikes unknown.
Tisp	**Porphyritic syenite dikes (Oligocene).** White to light gray and light tan potassium feldspar ± plagioclase porphyritic dikes. Potassium feldspar phenocrysts are 2 to 8 mm across, clear to white to pink in color, and subhedral, and compose up to 15% of the rock. Plagioclase phenocrysts are only 1-4 mm across, generally white, and occupy up to 5% of the rock. Fine (<1 mm across) biotite and amphibole phenocrysts are also locally present, and orangish brown iron oxide clots up to 5 mm across may be larger, but weathered, ferromags. Dike groundmass can be aphanitic, ‘milky’ smooth, and even crenulated (like **Tit** dikes), or are granular and composed of feldspars and fine rare ferromags. Dikes are up to 7 m wide.
Tiss	**Porphyritic syenite sills (Oligocene).** Light pink to light tan, potassium feldspar porphyry sills. Similar in appearance to the **Tisp** dikes described above, and in fact locally appear to be fed by **Tisp** dikes. Potassium feldspar phenocrysts are up to 3 mm across. Groundmass is granular and composed of potassium feldspar, plagioclase, and some ferromag. Up to 1 m thick.
Tif	**Felsite dikes (Oligocene).** White, fine-grained, aphyric, felsic dikes, 1 to 5 m wide; ages unknown.
Tim	**Megacrystal trachyte porphyry (Oligocene).** Greenish gray porphyritic dikes and sills with megacrysts of embayed hornblende and/or green pyroxene that are up to 2 to 4 cm across; groundmass contains hornblende ± biotite; may contain xenoliths of pink coarse-grained syenite; dikes may be up to 20 m across; ages of dikes unknown.

Mafic-intermediate dikes

Timd	**Monzodiorite dikes (Oligocene).** Light gray to medium gray weathering beige, potassium feldspar-, plagioclase-, amphibole-, and biotite-bearing phaneritic dikes. Dikes are identical in appearance to **Tipm** and are only located radiating from the margins of this stock, suggesting they are radial dikes associated with the **Tipm** intrusion. Dikes are up to 2 m thick.
Titp	**Trachyte porphyry dikes (Oligocene).** Light to dark gray porphyritic dikes with 15 to 25% plagioclase laths 10 to 20 mm long set in an equigranular to fine-grained matrix of dark green pyroxene and feldspar. The plagioclase laths are often distinctively aligned parallel to the margins of the dikes. Dikes are generally 1 to 4 m wide; ages of dikes unknown.
Tita	**Porphyritic trachyandesite dikes (Oligocene).** Dikes and small sills of light gray to purple gray porphyry with 5 to 15% of 1 to 10 mm diameter phenocrysts of plagioclase, dark green pyroxene, black hornblende, opaque oxides ± potassium feldspar; some dikes may grade into more equigranular textures (**Tig**). Dikes often contain syenitic and sedimentary xenoliths. Dikes in center and east are altered to silica, calcite, clay, chlorite and epidote. Dikes generally 1 to 12 m wide; ages of dikes unknown.
Tig	**Equigranular alkali gabbro-syenogabbro dikes (Oligocene).** Salt and pepper, fine- to medium-grained, equigranular dikes and small sills containing plagioclase and pyroxene phenocrysts; may grade into more porphyritic dikes (**Tita**). Generally 2 to 6 m wide; ages of dikes unknown.
Titb	**Aphyric trachybasalt dikes (Oligocene).** Dark gray aphanetic to sparsely finely porphyritic dikes. Phenocrysts, where present, are generally plagioclase. Locally, these dikes are spotted, similar to the trachybasalts of the **Twrtb_** units. Dikes are up to 1 m wide.
Titap	**Coarse-grained basaltic trachyandesite porphyry dikes (Oligocene).** Dark gray to purplish gray, coarse plagioclase-phyric porphyry dikes. Plagioclase phenocrysts are white rounded lathes 1 to 2 cm across and compose 20-40% of the rock. Dikes are also medium to coarse amphibole-phyric in places; these phenocrysts are black lathes 2-4 mm across, and compose up to 15% of the rock. Dikes are <1 to 3 m thick.

Coarse plagioclase lathes in a block of a Titap dike.

Tip **Plagioclase-phyric trachyandesite porphyry dikes (Oligocene).** Highly variable category of dikes. Includes medium to dark gray to purplish and bluish gray as well as greenish gray and tan, plagioclase ± amphibole porphyry dikes. Textures are highly variable, from fine (up to 1 mm across), sparse (up to 1%) plagioclase phenocrysts up through coarse (up to 9 mm aross) and/or abundant (up to 60%) plagioclase phenocrysts. Amphibole is absent to common (up to 30%), and fine to coarse (up to 5 mm across). Matrixes are generally aphanitic, but locally very fine granular. Dikes are usually thin (up to 1 m across), but can be up to 4 m thick.

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