ABSTRACT

Reconnaissance mapping along Copper Canyon highway has established ignimbrite stratigraphic relationships over a relatively large area in the central part of the Sierra Madre Occidental volcanic field in western Chihuahua, Mexico. The oldest ignimbrites are found in the central part of the area, and they include units previously mapped from north of the study area, in and around the Tomóchic volcanic complex. Copper Canyon, at the southern end of the study area, exposes younger units, including the intracaldera tuff of the Copper Canyon caldera and five overlying ignimbrites. Well-exposed calderas are found near San Juanito, in the central part of the map area, and at Sierra Manzanita, to the far north. Stratigraphic evidence for yet another caldera in the northern part of the area is found in the Sierra El Comanche. The stratigraphic and limited available isotopic age data suggest that volcanism was particularly active ~30 m.y. ago. This reconnaissance survey also documented lava-flow lithologies consistent with previous observations from Tomóchic that intermediate lavas have erupted throughout that area’s volcanic history and that basaltic andesite became particularly abundant as felsic volcanism waned. The combined Copper Canyon–Tomóchic area gives the first view into the core of the Sierra Madre Occidental volcanic field, Colorado.

Keywords: calderas, ignimbrite, Sierra Madre Occidental, volcanism, Mexico.

INTRODUCTION

The Sierra Madre Occidental volcanic Field

The Sierra Madre Occidental volcanic field (Fig. 1), from the United States–Mexico border to its intersection with the younger Mexican volcanic belt, covers at least 296,000 km² of western Mexico and is composed of lava and ignimbrite related to an estimated 350 major calderas (Swanson and McDowell, 1984). If exposures of equivalent age in southern Mexico are considered, the volcanic cover grows to ~393,000 km² (Aguirre-Díaz and Labarthe-Hernández, 2003). Although the general aerial extent and dominantly silicic composition of the Sierra Madre Occidental volcanic field has been known for more than a century (Ordóñez, 1896), detailed geologic maps showing ignimbrite cooling units and calderas did not appear until the 1970s (Swanson et al., 1978). Since that time, a series of “discovery-phase” mapping projects have progressed, mainly along the major access routes crossing and flanking the area. Notably, these are the Guadalajara-Zacatecas and Guadalajara-Fresnillo highways and connecting roads in the southern Sierra Madre Occidental (see Nieto-Samaniego et al., 1999; Ferrari et al., 2002), the Durango-Mazatlán highway in the central part of the range (see McDowell and Clabaugh, 1979), and the El Paso–Chihuahua and Chihuahua-Hermosillo highways of the northern Sierra Madre Occidental (see McDowell and Mauger, 1994; Swanson and McDowell, 1985; Cochemé and Demant, 1991; McDowell et al., 1997).

These studies, and others, have shown that the Sierra Madre Occidental volcanic field consists of a relatively unfaulted central core of Tertiary volcanic rock, framed by NNW-trending normal faults that enter Mexico from the Basin and Range Province of the southwestern United States, diverge around the core of the Sierra Madre Occidental, and recombine at the southern end of the mountain range (Henry and Aranda-Gómez, 1992; Ferrari et al., 2002). Several periods of faulting have been identified (Nieto-Samaniego et al., 1999; Henry and Aranda-Gómez, 2000; Ferrari et al., 2002).

Studies, mostly from the west side of the Sierra Madre Occidental, reveal that western Mexico has experienced a lengthy, subduction-related magmatic history (see Roldán-Quintana et al., 2003; Ferrari et al., 2005). This includes the emplacement of Cretaceous to early Tertiary batholithic rocks and the widespread eruption of the coeval, but relatively unstudied, andesite and rhyolite informally known as the lower volcanic complex (McDowell and Keizer, 1977). Subduction-related volcanism culminated with massive outpourings of mid-Tertiary volcanic rocks, mostly ignimbrite (informally the upper volcanic supergroup of McDowell and Keizer, 1977), which were emplaced toward the end...
of Farallon–North America plate convergence. Ignimbrite volcanism in the core of the volcanic field began as early as 38 Ma (Wark et al., 1990), and volcanism appears to have become extremely voluminous just prior to abruptly terminating over most the Sierra Madre Occidental volcanic field at 28 Ma. Younger ignimbrites (ca. 24–21 Ma), however, are found in a belt along the western flank of the volcanic field that expands southward to cover much of the southern Sierra Madre Occidental (see Ferrari et al., 2002; Roldán-Quintana et al., 2003). Basaltic andesite lava flows, the Southern Cordilleran Basaltic Andesite, or SCORBA, of Cameron et al. (1989), appear to be widespread throughout the range and are commonly found intercalated with, or overlying, each area's youngest ignimbrites. Mechanisms explaining the timing, petrogenesis, and extreme volume of the Sierra Madre Occidental volcanic field have focused on a change in stress regime from compression to one of extension (Wark et al., 1990) and on a transient thermal event possibly triggered by the Farallon slab with resulting exposure of the overriding plate to hotter asthenospheric mantle (Ferrari et al., 2002).

All current tectonic and petrogenetic interpretations rely on the “discovery-phase” mapping begun in the 1970s. While much progress has been made toward understanding the origin of rocks of the Sierra Madre Occidental, we estimate that more than 90% of this great volcanic field remains unmapped and that fewer than 10% of its calderas have been identified. Mapped areas in the central Sierra Madre Occidental are particularly sparse, and for over 1000 km along the length of the field, except for very narrow transects along the Durango-Mazatlán highway, the Chihuahua-Hermosillo highway, and along highways north of Guadalajara, the core of the Sierra Madre Occidental volcanic field is virtually unknown. This paper presents new information on ignimbrites and their source calderas for a large area in the heart of the Sierra Madre Occidental, giving a view into the geologic core of this great volcanic field and providing information needed for more detailed studies of all descriptions.

Western Chihuahua

Mexican national highway 16 (here called the Chihuahua-Hermosillo highway) has previously served as the locus for a series of mapping projects across the northern part of the Sierra Madre Occidental volcanic field. These include the Tomóchic area (Fig. 2) in the core of the range, where two overlapping calderas and six major ignimbrite formations with K-Ar ages ranging in age from 38 to 29 Ma are found (Swanson and McDowell, 1985; Kempter, 1986; Wark et al., 1990). Wark (1991) also studied the petrogenesis of Tomóchic volcanic center rocks, emphasizing a genetic relationship between the large-volume rhyolite ignimbrites and more mafic lithologies, the dominant role played by crystal fractionation, and the temporal relationship between rhyolite volcanism and the waning stages of Farallon plate subduction. A study of the isotopic composition of Tomóchic volcanic rocks (McDowell et al., 1999) indicated that Laurentian basement, like that in the southwestern United States, does not extend under

Figure 1. Major exposures of Tertiary volcanic rocks of the Sierra Madre Occidental volcanic field and of adjacent regions in Baja California, Arizona, New Mexico, Texas, and in southwestern Colorado (inset at the same scale). Outcrop pattern is adapted from Swanson and McDowell (1984), and modified by information from Ferrari et al. (2002).
the area. Results from a regional isotopic study (Housh and McDowell, 2005) are compatible with the region being underlain by a Proterozoic basement and Paleozoic arc sequence accreted to the southern margin of the North American craton during Ouachita convergence. A surface-wave study using seismic waves generated below the Gulf of California and recorded in Texas has indicated a crustal thickness of 55 km for the northern part of the central core of the Sierra Madre Occidental volcanic field (Bonner and Herrin, 1999).

Chihuahua highway 127 (here called the Copper Canyon highway) diverges from the Chihuahua-Hermosillo highway, passes 50 km south of the Tomóchic volcanic center, and extends southwestward to the rim of Copper Canyon (Fig. 2). Yet another highway is being completed between Creel and Batopilas, the site of the nearest mapped area to the south (Bagby, 1979). As a result, a large area of the core of
the volcanic field has become open to geologic investigation. Our reconnaissance mapping identified well-preserved calderas in the Sierra Madre Occidental and near San Juanito (Fig. 2). Evidence for two other calderas was also found, and the area’s ignimbrite stratigraphy has been correlated with that at Tomóchic. The combined Tomóchic–Copper Canyon area reveals that the core of the Sierra Madre Occidental contains a stratigraphic section that is typically thicker and more complex than those known from the periphery of the volcanic field.

**STRATIGRAPHY**

**Introduction**

The Sierra Madre Occidental is commonly described as an elevated volcanic plateau, and much of the range is plateau-like in form as a consequence of ignimbrite volcanism. The plateau, however, does contain significant local relief. The Copper Canyon area, for example, exhibits extensive plateaus at elevations between 2200 and 2400 m, with mountains rising 400–700 m above, and canyons cutting 1 km or more below these plateaus. Given such relief, and considering that 1 km is a commonly reported thickness for the silicic volcanic cover, sections exhibiting good stratigraphic information might reasonably be expected. Such sections, however, are rare. Mountain masses rising above the plateau are typically composed of lava sequences or a lava dome complex, but a few consist of massive intracaldera ignimbrite.

Canyons that dissect the mesas also tend to reveal only single thick ignimbrites or volcaniclastic sequences, possibly filling older caldera structures. Sections exposing multiple, diverse ignimbrite outflow units are sparse in the Copper Canyon area. It may be that this is typical of the central axis of the Sierra Madre Occidental, but it is unlike fringing regions such as Durango (Swanson et al., 1978) or central Chihuahua (see McDowell and Mauger, 1994), where extensive regions display “layer-cake” stratigraphy. The most diverse stratigraphic sections currently known from the core of the northern sierra are along the eastern topographic margin of the Tomóchic caldera (Swanson and McDowell, 1985; Wark et al., 1990) and near Divisadero, were Copper Canyon slices 1.4 km into the sierra plateau (Fig. 3).

From Divisadero’s excellent exposures northward to the village of San Juanito, two-thirds of the distance across the Copper Canyon area, little but the upper part of the stratigraphic sequence can be seen. Exposures in the central part of the area, however, do shed light on the stratigraphic relationship between the Copper Canyon and Tomóchic areas, and they also reveal the newly discovered San Juanito caldera (Fig. 2). The rugged northeastern third of the Copper Canyon area contains the Sierras El Comanche and Manzanita (Fig. 2); each range is dominated by a single major ignimbrite overlain by complexly interlayered sedimentary rock and lava. From south to north, therefore, the study area is naturally segmented into southern (Divisaderocreek), central (Creel–San Juanito), and northern (Comanche-Manzanita) sections, and the stratigraphic relationship is discussed in terms of these subareas (Fig. 2). The various calderas will be discussed in a later section.

**Southern Section: Divisadero to Creel**

Divisadero, on the southern side of the narrow divide between the Rio Oteros and the Rio Urique (Fig. 4), overlooks Copper Canyon and the Rio Urique nearly 1400 m below. Divisadero is also the site of the only previous work in the area, that of Achim Albrecht, who examined and sampled Copper Canyon rocks as part of a geochemical study aimed at understanding basement rocks of northwestern Mexico (Albrecht and Brookins, 1989; Albrecht, 1990; Albrecht et al., 1990; Albrecht and Goldstein, 2000). Albrecht sampled rocks along a trail just outside our map area to the south, but the region’s ignimbrite units are much better exposed along a trail down from Mesa Mogotabo (Figs. 3 and 4).

Six distinctive major ignimbrites have been identified in the 1400-m-thick Mogotabo stratigraphic section (Figs. 3 and 4). The basal 1025 m consists of an extraordinarily thick ignimbrite informally named the Copper Canyon tuff. Five different conformable ignimbrite units with thicknesses typical of outflow units constitute most of the upper 375 m of the section. These units are exposed near Divisadero as two relatively thin layers, two relatively thick overlying units, and a densely welded capping tuff, of which only a thin remnant remains along the mesa rim (Fig. 3). The Mogotabo section is described from the base upward in the following sections.

**Unit 1—Copper Canyon Tuff**

The Copper Canyon tuff is presently known only from the depths of Copper Canyon, where an 800 m thickness (base not exposed) of dark, cliff-forming ignimbrite grades upward to a thick, whitish top, forming a total exposed thickness of ~1 km (Fig. 3). Although indications of layering and cooling breaks can be seen in cliff-face exposures, most observations support this simple relationship. A densely welded sample obtained from the trail south of Divisadero is dark red and extremely crystal-rich (approaching 50%). Its phenocryst assemblage consists of plagioclase (2–4 mm), embayed and broken grains of quartz (2–3 mm), biotite (to 1.5 mm), and a minor amount of hornblende. The rock is generally altered, and the pyroclastic nature is not always immediately apparent at the outcrop. The upper 200 m is composed of a white to lavender ignimbrite locally containing abundant, white, spuerilitically devitrified pumice, some lithic fragments, and distinctly fewer total phenocrysts.

Observations from the canyon rim and from helicopter reconnaissance show that the Copper Canyon tuff with its prominent white top can be seen throughout the canyon. Although indicators such as caldera collapse megabreccias and moat sedimentary sections are not seen at Mogotabo, the exposed thickness of 1 km strongly suggests that the Copper Canyon tuff lies within its source caldera. The Rio Urique, it seems, has cut through younger ignimbrites from various other sources to become entrenched into the intra-caldera ignimbrite of what we designate as the Copper Canyon caldera (Fig. 2). As commonly seen with intracaldera ignimbrites (see Lipman, 1984), the densely welded, lower part of the unit displays prominent, closely spaced, vertical joints. These generally strike NW at nearly right angles to Copper Canyon at Divisadero, and it seems probable that this joint system is the structural control for the distinctive right-angle turn of the Rio Urique seen just upstream from Divisadero (Fig. 2).

**Unit 2**

The Copper Canyon tuff is over lain at the Mogotabo section by a thin (24 m), densely welded ignimbrite informally called unit 2 (Figs. 3 and 4). A basal vitrophyre, ~1 m in thickness, passes upward to a red, eutaxitic ignimbrite with a moderate percentage (~25%) of phenocrysts, which consist of relatively large plagioclase (2–3 mm), fairly abundant clinopyroxene, and minor hornblende phenocrysts enclosed in reddish shards. Lithic fragments and small pumice are fairly common, and the rock remains densely welded to its top.

**Unit 3**

The third ignimbrite up from the base of the Mogotabo section is ~60 m thick and grades from a densely welded, reddish brown, cliff-forming rock to a soft, white top seen forming a slope between hard ignimbrite ledges (Fig. 3). The rock contains ~20% phenocrysts, mostly plagioclase (to ~3 mm) and biotite (to ~2 mm), set in distinctively reddish shreds. Small pumice and lithic fragments are common.

**Unit 4**

Unit 4 at Mogotabo was measured at 86 m thick. Rock low in the unit is light reddish brown...
Figure 3. Photo composite of the view looking northward toward ignimbrite units exposed in the Mogotabo section at Copper Canyon.
to pink, and eutaxitic with blue-gray streaks. As with unit 3, a poorly welded, white top is preserved. The rock has relatively thin, clear shards, and a low to moderate percentage of phenocrysts (~20%), consisting mostly of plagioclase and biotite. Units 3, 4, and 5 also appear somewhat up-canyon along tributaries leading toward Copper Canyon (Fig. 4).

**Unit 5**

Mogotabo’s unit 5 is ~80 m in thickness, and this simple cooling unit is separated from unit 4 below by ~30 m of soft, underlying, biotite-rich ignimbrite. Unit 5 is typically pale orange or reddish brown (more strongly colored where densely welded) and grades upward to a poorly welded, light-gray or white top. The rock is characterized by a low phenocryst content (~10%), consisting of plagioclase and biotite set in a groundmass of rather large, thick, clear shards. Lithic fragments are rare. Where devoid of pumice, unit 5 is a homogeneous, massive, reddish-orange ignimbrite that tends to break along smooth, curved fractures. Pumice, however, is locally abundant in unit 5, and distinctively bright rims commonly outline these pumice fragments. Thin-section examination reveals the bright rims to contain fine-scale, spherulitic devitrification surrounding darker pumice cores that exhibit more coarsely crystalline spherulitic or granophyric devitrification. Elsewhere, entire pumice fragments may be either light or dark, perhaps reflecting compositional differences. Unit 5 is overlain at the Mogotabo section by ~90 m of volcaniclastic and pyroclastic rock, perhaps reflecting compositional differences.

Figure 4. Geologic map of the southern section from Divisadero to Creel. MSL—mean sea level.

**Divisadero Tuff: Divisadero to Creel**

The 10 m thickness of Divisadero tuff capping the Mogotabo section is but a thin, erosional
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remnant of an extremely widespread unit of great local thickness and complexity. A more typical thickness of the ignimbrite along this part of the canyon rim is exposed at Divisadero, where the unit takes its name. There, the Divisadero tuff consists of two ignimbrite cooling units, whitish to pink in color, in which relatively large pumice and lithic fragments (including plutonic rocks) are found in abundance. The ignimbrite contains ~40% phenocrysts, which consist mostly of sizable (to 4 mm) grains of plagioclase and deeply embayed and broken quartz (to 4 mm), while the hydrous mafic minerals, biotite and hornblende, are also common.

The Divisadero tuff at Mogotabo thins northward and overlies rocks of the nearby Cerro Huerarachi rhyolite flow dome. The unit then increases in thickness and complexity northward toward Creel, as crystal-rich cooling units both overlie and underlie local felsic flow-dome rhyolite, minor volcanlastic sequences, some poorly welded tuffs, and mafic lava. Except for these local disruptions, the Divisadero tuff forms a widespread resistant cap to the ignimbrite section from Divisadero to Creel and beyond (Fig. 4).

Central Section: Creel to San Juanito

The Copper Canyon highway from Creel to San Juanito continues the pattern of extensive mesas formed on Divisadero tuff, interrupted locally by rugged topographic highs developed on felsic flow-dome complexes (Fig. 5). The San Felipe, Vista, and Rio Verde tuffs, units known from mapping of the Tomóchic area (Kempter, 1986), are exposed northwest of the San Juanito caldera (Fig. 5). Exposures, however, along the upper reaches of the Rio Conchos (locally called the Rio de Bocoya) are particularly instructive because they shed light on the stratigraphic relationship between the Copper Canyon and the Tomóchic areas (Fig. 5).

Vista and Rio Verde Tuffs

The Vista tuff and overlying Rio Verde tuff described from the Tomóchic area by Swanson and McDowell (1985) were interpreted as having erupted from the Tomóchic volcanic complex at 34.1 and ca. 31.5 Ma, respectively (Wark et al., 1990). Both units are locally exposed northeast of the San Juanito caldera and along the Rio Bocoya below yet another mesa capped by Divisadero tuff (Fig. 5). The Vista tuff, with its readily visible quartz, abundant feldspar, biotite, and hornblende, is nearly identical in appearance to the Divisadero tuff as seen at Copper Canyon and at Bocoya. While thin-section examination reveals that some Vista cooling units carry sanidine and that all units contain a small amount of titanite (typically about one grain per thin section), distinguishing between the Vista and Divisadero tuffs in the field can pose a problem. At Bocoya, however, the Divisadero tuff is clearly seen to overly both the Vista and Rio Verde tuffs, establishing it as a younger, separate ignimbrite (Fig. 5).

Kempter (1986) and Wark et al. (1990) described the Rio Verde tuff from the Tomóchic area as consisting of four similar-looking members that are typically thin, highly welded and with basal vitrophyres. The second-oldest member of the formation was distinguished by its plagioclase-pyroxene phenocryst mineralogy, its reddish color, and especially by its distinctive vuggy nature. A single cooling unit of Rio Verde tuff crops out above the Vista tuff north of Bocoya, and samples from Bocoya are indistinguishable from the second member of the Rio Verde Tuff at Tomóchic. Rio Verde ignimbrite at Bocoya, as at Tomóchic, was deposited over a surface of significant paleorelief. This is seen along the Rio de Bocoya, for example, as the unit thins dramatically southward, pinching out in the direction of a felsic flow-dome complex just south of Bocoya (Fig. 5).

Mogotabo Units 3 and 5

Mogotabo units 3 and 5 are found in the southern moat of the San Juanito caldera. Unit 3 there has a thickness similar to that at Mogotabo, but it displays a thin basal vitrophyre in exposures along the southern flank of the San Juanito caldera’s resurgent dome. Exposures of unit 5 are somewhat thinner, less welded, and less eutaxitic than at Mogotabo, but they maintain their distinctive low percentage of biotite and plagioclase phenocrysts, and locally their light- and dark-color pumice and pumice with distinctively bright pink rims. Exposures of the unit are particularly good on Mesa Quemada (Fig. 5), and the unit is henceforth referred to as the Quemada tuff.

There are obvious stratigraphic complexities in the Copper–San Juanito area. The Divisadero tuff, for example, can variously be found directly overlying either the Quemada, the Rio Verde, or the Vista tuffs. Also, neither the Copper Canyon tuff nor Mogotabo unit 2 or 4 has been identified in the area, and there is a large area west of El Ranchito (Fig. 5) that contains a very thick ignimbrite that remains uncorrelated with any known units. The Divisadero tuff also shows considerable internal variations, here and throughout its known exposures.

Divisadero Tuff

The phenocryst-rich Divisadero tuff forms a resistant cap for nearly 20 km between Bocoya and San Juanito (Fig. 5), as well as underlying the previously mentioned mesas between Divisadero and Creel, a total road distance of 75 km. It is the region’s most widespread unit, and it will be discussed in more detail later. Reconnaissance traverses tens of kilometers southeastward on side roads from Creel toward Batopilas, from Bocoya toward Panalachi, and between San Juanito and Carichi (Fig. 2) indicate that multiple cooling units of crystal-rich ignimbrite form an extensive plateau throughout the upper Rio Urique and the upper Rio Conchos river valleys. The unit can be exceptionally thick. At least five separate cooling units can be observed from the mesa overlooking Creel to the bottom of the nearby Rio Conchos to the south, a vertical drop of 300 m (Fig. 4). The Divisadero tuff locally contains intercalated lava or sedimentary rocks. These rocks and the unit’s radical local thickness variations show that the various cooling units were erupted over a surface of significant topographic relief caused by erosion, lava-dome emplacement, and probably by prior caldera formation as well. Regionally, this ignimbrite package thickens dramatically eastward from the Copper Canyon highway into the Conchos and Urique drainage basins (Fig. 2).

The Divisadero tuff as mapped in this reconnaissance study consists of units sharing a crystal-rich nature and high stratigraphic position. Although we found it impossible to separate them at a reconnaissance level, the various Divisadero cooling units display sufficient variations to suggest that genetically different units may well have been included. Individual Divisadero cooling units, for example, display somewhat different phenocryst minerals, and our samples fall into three types. Ignimbrite exposed at Divisadero is quartz-rich and contains the mafic minerals biotite and hornblende, as does Divisadero tuff in the San Juanito–Bocoya area. The Divisadero tuff capping the extensive mesa in the southern section between Creel and Arroyo Puerto Blanco (Fig. 4) is similar, except that pyroxene joins the mafic mineralogy. This Divisadero cooling unit overlies a third phase in which quartz is not easily recognizable in hand specimen, biotite is the only mafic mineral, and the total phenocryst content tends to be lower. Even this type, however, is locally crystal-rich. Quartz-poor Divisadero is widely exposed along the broad mesa areas between Pitorreal and in Arroyo Puerto Blanco (Fig. 4), where it and the overlying quartz-rich variety dip toward and thicken dramatically in the direction of Copper Canyon. Some Divisadero tuff, as at San Juanito, is relatively devoid of lithic fragments and pumice, while pumice is common elsewhere, and lithics, including granitoid rocks, can be found to 0.5 m in diameter.
Figure 5. Geologic map of the central section from Creel to San Juanito, showing the San Juanito caldera centered on Cordon Cumbre Alta, 15 km northwest of the town of San Juanito.
IGNIMBRITES AND CALDERAS OF THE COPPER CANYON AREA

These differences aside, Divisadero cooling units typically grade from densely welded red to purple (or lavender) bases to less welded, brownish or whitish tops. White tops, if preserved, are typically massive and poorly vegetated, while brownish tops tend to weather into hoodoo forms like those seen in the bluffs around Creel and at the nearby tourist attraction of the Valle de los Monjes (Valley of the Monks) overlooking the Rio Conchos (Fig. 4).

In summary, multiple phenocryst-rich units exhibiting a range of phenocryst mineralogy and with detailed stratigraphic relationships obscured by profound lateral thickness variations form a resistant ignimbrite cap to mesas from Divisadero to San Juanito (Figs. 4 and 5) and eastward across wide regions of the upper Rio Conchos and Urique drainage basins. Lithic blocks near Copper Canyon locally reach 0.5 m in diameter, and as the area’s youngest major ignimbrite sequence, its caldera source(s) might be expected to be among the most obvious, but we did not discover evidence for that caldera in the study area.

Northern Section: Sierra Manzanita and Sierra El Comanche

The Sierras Manzanita and El Comanche constitute the northeastern limit of the study area (Fig. 6), and they may also mark the eastern margin of the relatively undisrupted structural core of the Sierra Madre Occidental volcanic field. Exposures farther east have been strongly affected by Basin and Range faulting. The lack of ignimbrite diversity has frustrated efforts toward making regional stratigraphic relationships.

Figure 6. Geologic map of the northern section covering Sierra El Comanche and the Sierra Manzanita, showing the Manzanita caldera.
correlations for the Sierra El Comanche, but not for the Sierra Manzanita. That mountain mass mostly consists of a reddish, vitric ignimbrite containing the sparse plagioclase-biotite mineralogy, the large, clear shards, and distinctive pumice of the Quemada unit (Mogotabo’s unit 5). The thickness of the Quemada tuff in the Sierra Manzanita, together with other evidence for a caldera (discussed later), identifies this as its intracaldera facies. The larger and loftier Sierra Comanche contains two ignimbrites of less certain origin, which are informally named the Alamito and El Comanche tuffs.

**Alamito and El Comanche Tuffs**

The Alamito tuff is the oldest ignimbrite recognized in the Sierra El Comanche. It was found at two locations, a small exposure along the highway near El Alamito, and an exposure of several kilometers length along an arroyo just upstream from El Alamito (Fig. 6). The Alamito tuff is a red to orange-red, eutaxitic, densely welded ignimbrite containing ~25% phenocrysts, including fairly large plagioclase (to 4 mm) and relatively abundant clinopyroxene, but no biotite. The exposure along the Copper Canyon highway shows the highly distorted foliation typically attributed to postemplacement, downslope rheomorphic flow.

The Alamito tuff is overlain by El Comanche tuff, which passes upward from a thick basal vitrophyre to a brick-red, extremely eutaxitic ignimbrite. Thin sections of El Comanche tuff show distinctly thin shards and fewer phenocrysts (~20%) than the Alamito, but its mineralogy (plagioclase + clinopyroxene) is the same. El Comanche tuff also displays rheomorphic folds.

The Copper Canyon highway from Rancho Blanco to El Nogal (Fig. 6) traverses the southern periphery of Sierra El Comanche where it passes through the purple, less-welded, upper part of El Comanche tuff, which contains compressed pumice fragments to 0.5 m in length. The ignimbrite dips gently away from Sierra El Comanche to pass beneath a sequence of lavas (rhyolite to andesite), various soft tuffs, and volcaniclastic sedimentary rocks flanking the southeastern side of the range. Northwest, into the Sierra El Comanche, the unit’s exposed thickness is several hundred meters, and it is overlain along the northern flank of the range by an equally thick sequence of lava rock. The thickness of the Comanche tuff in this area is suggestive of an intracaldera setting (discussed later).

**Isotopic Age Information**

Isotopic age information is reported for two area ignimbrites, the Copper Canyon and Divisadero tuffs, and for a lava flow from within the San Juanito caldera. The Copper Canyon tuff is the basal unit of six ignimbrite formations exposed at Copper Canyon below Divisadero. A sample from along the south trail down from Divisadero (Fig. 4) was dated by \(^{40}\)Ar/\(^{39}\)Ar method at the New Mexico Geochronology Research Laboratory. Samples of Divisadero tuff, the unit which caps the stratigraphic section at Copper Canyon and which forms ignimbrite-capped mesas across much of the study area, were collected near Creel (Fig. 4). The Divisadero samples along with lava collected from the San Juanito caldera (Fig. 5) were dated by K-Ar at the University of Texas at Austin using conventional techniques; Ar was analyzed by isotope-dilution mass spectrometry, and K was analyzed by flame photometry or inductively coupled plasma–mass spectrometry (ICP-MS). \(^{40}\)Ar/\(^{39}\)Ar ages were obtained at the New Mexico Geochronology Laboratory. See appendix (see footnote 1) for details.

**TABLE 1. GEOCHRONOLOGY: COPPER CANYON AREA VOLCANIC ROCKS**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Sample</th>
<th>%K</th>
<th>(^{40})Ar* (10^6 scc/g)</th>
<th>(^{40})Ar* (±1σ)</th>
<th>Age (Ma)</th>
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<td>Felsic lava</td>
<td>N 63</td>
<td>6.939</td>
<td>64.9</td>
<td>7.961</td>
<td>29.4 ± 0.5</td>
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<td>7.510</td>
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<tr>
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<td>65.2</td>
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<td>Divisadero tuff</td>
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<td>70</td>
<td>8.08</td>
<td>29.8 ± 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.05</td>
<td>72</td>
<td>8.27</td>
<td></td>
</tr>
</tbody>
</table>

**40Ar/39Ar analyses**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Mineral</th>
<th>Analysis</th>
<th>N</th>
<th>MSWD K/Ca</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>biotite</td>
<td>Plateau</td>
<td>11</td>
<td>1.3</td>
<td>29.62 ± 0.32</td>
</tr>
<tr>
<td>Divisadero tuff</td>
<td>hornblende</td>
<td>Mean</td>
<td>6</td>
<td>3.6</td>
<td>28.84 ± 0.58</td>
</tr>
</tbody>
</table>

Note: Sample locations are shown on area geologic maps (Figs. 4 and 5). K-Ar ages were obtained at the University of Texas at Austin using conventional techniques; Ar was analyzed by isotope-dilution mass spectrometry, and K was analyzed by flame photometry or inductively coupled plasma–mass spectrometry (ICP-MS). \(^{40}\)Ar/\(^{39}\)Ar ages were obtained at the New Mexico Geochronology Laboratory. See appendix (see footnote 1) for details.

**Geosphere, May 2006**
El Comanche (Fig. 7).

4 are separated by a relatively thin ignimbrite of plagioclase-biotite mineralogy (unit 3), and that it must be noted that Mogotabo units 2 and 4 at Mogotabo. The petrographic grounds that its distinctively large plagioclase-pyroxene ignimbrites, nearly all of which have preserved, poorly welded tops and generally lack interlayered sedimentary rocks. The stratigraphic evidence at Mogotabo indicates rapid emplacement of units with little intervening time for either erosion or deposition. The limited available age information supports this interpretation and also indicates that the entire Mogotabo section postdates the Vista and Rio Verde tuffs (Fig. 7).

The thick Copper Canyon tuff at the base of the Mogotabo section has not been identified elsewhere in the area. Biotite-bearing, Mogotabo units 2 and 4 are both found in the central section, within the moat of the San Juanito caldera, where unit 5 is recognized as the Quienada tuff (Fig. 7). The source for unit 3 is not known, but the Quienada tuff’s intracaldera facies is located in the northern section’s Sierra Manzanita (Fig. 7). The Quienada tuff, then, is the only unit known from all three sections of the Copper Canyon strip.

Mogotabo units 2 and 4 each possess a plagioclase-pyroxene phenocryst mineralogy, as do the Alamito and El Comananche tuffs of the northern section. The only other known plagioclase-pyroxene ignimbrites in the region are some cooling units of the Rio Verde tuff and the previously unmentioned Heredia tuff. Petrographically, the Rio Verde tuff is a poor match for either Mogotabo ignimbrite, and it can also be dismissed on the basis of the Tomóchic area, but can also be dismissed on the basis of the Estación highway southwest of Rancho Blanco, both of which are located on the flanks of the Sierra Manzanita. Mogotabo units 2 and 4 are separated by a relatively thin ignimbrite of plagioclase-biotite mineralogy (unit 3), and that no such unit is presently known from the Sierra El Comananche (Fig. 7).

### Area Lava Rock

Lavas ranging in composition from mafic to felsic cover ~30% of the map area (Figs. 4, 5, and 6), and reconnaissance east of San Juanito indicates that mafic lavas cover an even higher percentage of the area there. While much of this lava clearly fits within the framework of known or postulated calderas, older caldera structures are likely obscured by these late-stage lavas and related pyroclastic deposits. The Road to Copper Canyon crosses felsic lava domes and related pyroclastic deposits north of San Juanito, south of Bocoyana, in and around Creel, at Cerro Los Hoyitos, and at its approaches Copper Canyon at Divisadero (Figs. 4 and 5). Similar rock is found on the eastern and western sides of the San Juanito caldera as well as at various places within the Manzanita caldera and Sierra El Comananche (Figs. 5 and 6). All of these felsic lavas have intertextal textures, and although almost all are sparsely populated with phenocrysts of plagioclase and biotite, a few also contain clinopyroxene. Phenocryst-rich, quartz and/or sanidine-bearing lavas are found capping the Cerro de la Luna immediately north of the San Juanito caldera, and near the Copper Canyon highway southwest of Rancho Blanco, both of which are located on the flanks of the Sierra El Comananche (Figs. 5 and 6). Cerro Neychupicha (Fig. 5), rising some 230 m immediately east of San Juanito, is composed of less felsic-looking, pyroxene-plagioclase-bearing lava erupted over the Divisadero tuff. Similar-looking lava is

<table>
<thead>
<tr>
<th>TABLE 2. AREA IGNIMBRITE UNITS</th>
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<tbody>
<tr>
<td><strong>Unit</strong></td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>Cueva tuff</td>
</tr>
<tr>
<td>Poorly welded, light-colored, pumice-bearing, multiple cooling units form massive deposits near Tomóchic.</td>
</tr>
<tr>
<td>Heredia tuff</td>
</tr>
<tr>
<td>Strongly welded, red, two cooling units with basal vitrophyres, ~50 m thick, lithics, large phenocrysts, rheomorphic.</td>
</tr>
<tr>
<td>Divisadero tuff</td>
</tr>
<tr>
<td>Strongly welded, red to brown, multiple cooling units, highly variable thickness to more than 300 m, lithics and pumice locally abundant, may lack q and/or cpx, poorly welded top commonly forms hoodoo.</td>
</tr>
<tr>
<td>Mogotabo Unit 4</td>
</tr>
<tr>
<td>Strongly welded, orange or red grading upward to gray, 80 m thick at Mogotabo (Mogotabo unit 5), may show pumice in two colors or pumice with bright rims, large clear shards, erupted from Manzanita caldera.</td>
</tr>
<tr>
<td>Mogotabo Unit 3</td>
</tr>
<tr>
<td>Strongly welded, eutaxitic with red-brown and blue-gray streaks, 86 m thick at Mogotabo, thin section shows thin clear shards, resembles the thick, rheomorphic El Comananche tuff at Sierra El Comanche.</td>
</tr>
<tr>
<td>Mogotabo Unit 2</td>
</tr>
<tr>
<td>Strongly welded, red, 24 m thick at Mogotabo, eutaxitic with reddish shards and a basal vitrophyre, lithics and pumice common, resembles the locally rheomorphic Alamito tuff of Sierra El Comanche.</td>
</tr>
<tr>
<td>Copper Canyon tuff</td>
</tr>
<tr>
<td>Strongly welded, red grading upward to prominent white top, some lithics and pumice, known only from Copper Canyon where a &gt;1 km thickness suggests its source caldera.</td>
</tr>
<tr>
<td>Rio Verde tuff</td>
</tr>
<tr>
<td>Strongly welded, red, commonly displays two cooling units, ~50 m total thickness, lithophysal cavities and basal vitrophyres are common, previous work suggests Tomóchic caldera as the source.</td>
</tr>
<tr>
<td>Vista tuff</td>
</tr>
<tr>
<td>Moderately welded and light gray but can be strongly welded and red, multiple cooling units recognized locally, rare basal vitrophyre, outflow thickness 50–400 m, erupted from Las Varas caldera.</td>
</tr>
<tr>
<td>San Felipe tuff</td>
</tr>
<tr>
<td>Strongly welded, streaky lavender and white, to multiple cooling units and 300 m thick, basal vitrophyre common, extremely eutaxitic, some lithics, resembles the intracaldera tuff of San Juanito caldera.</td>
</tr>
<tr>
<td>Cacabelo tuff</td>
</tr>
<tr>
<td>Poorly to moderately welded, lavender, at least 70 m thick with base not exposed, andesitic lithics common.</td>
</tr>
</tbody>
</table>

*Note: Ignimbrite units are arranged stratigraphically according to present state of knowledge. Ph. E.—plagioclase, q.—quartz, b.—biotite, s.—sanidine, cpx.—clinopyroxene, hbl.—hornblende, ti.—titanite. N.D.—not determined.*
Figure 7. Regional ignimbrite correlation diagram showing the relative geographic position of the various areas discussed, the ignimbrite units exposed in each area and the suggested regional correlations as discussed in the text. Note the tentative correlation between units 2 and 4 of the southern area and the northern area’s Alamito and El Comanche tuff.
abundantly found high in the section throughout the Sierra Comanche.

Hornblende-bearing andesite forms a partial cap to the San Juanito caldera’s resurgent dome. Some pyroxene andesite is also found there, and precalderas, clinopyroxene-plagioclase andesite covers a wide area along the northern rim of the San Juanito caldera. The situation seems similar to that at Tomóchic, where Wark (1991) found that intermediate magmas had been present throughout volcanic activity at the Tomóchic volcanic complex.

Mafic lava, similar in appearance and stratigraphic position to Southern Cordilleran Basaltic Andesite (SCORBA) as defined by Cameron et al. (1989), is common throughout the Copper Canyon area (Figs. 4 and 5). Its occurrence there is like that previously noted at Tomóchic (Wark et al., 1990; Wark, 1991), where mafic lava was found to be particularly abundant high in the stratigraphic section yet still interlayered with ignimbrite or rhyolite lava. A few dikes of similar composition are found in the Copper Canyon area (Fig. 4). Again, this is similar to the Tomóchic area, where NW- to NNE-trending dikes, trends similar to younger normal faults, suggest eruption during regional extension. A reconnaissance traverse from San Juanito eastward to Carichi (70 km by road) showed that much of the intervening area of the Sierra is covered by basaltic andesite, including thick accumulations of olivine-bearing lava, as in Cerro Rumurachi rising 500 m above the plateau surface. Certainly this late, thick lava covering makes it difficult to recognize older caldera structures in this region and possibly over vast regions in the core of the Sierra Madre Occidental volcanic field.

CALDERAS OF THE COPPER CANYON AREA

Previous Work—The Tomóchic Volcanic Center

Although calderas have been previously proposed for several locations in the northern part of the Sierra (see Swanson and McDowell, 1984), the best-documented calderas are those of the Tomóchic volcanic center (Fig. 2) (Swanson and McDowell, 1985; Wark et al., 1990; Wark, 1991; McDowell et al., 1999). The Tomóchic volcanic center includes the Tomóchic and Las Varas calderas. Las Varas caldera formed ca. 34 Ma during eruption of the Vista tuff, and its exposed intracaldera facies is cut by the northern structural margin of the Tomóchic caldera. With its prominent central dome, surrounding moat, and ring-fracture rhyolite, Tomóchic caldera neatly fits the classic resurgent caldera model except that its resurgent dome is completely mantled by younger, probably resurgence-related volcanic rocks. With no exposed intracaldera ignimbrite, the identity of the erupted ignimbrite has remained problematic.

All previous published work has related Tomóchic caldera formation to eruption of the 31.7 Ma Rio Verde tuff. This correlation is based primarily on the Rio Verde tuff being the youngest ignimbrite of any consequence exposed along the caldera’s topographic rim. Yet, caldera resurgence doming and ring-fracture volcanism are dated at ca. 29–30 Ma (Swanson and McDowell, 1985; Wark et al., 1990). The only unit overlying the Rio Verde tuff near Tomóchic is the informally named Cueva tuff. While its ca. 29 Ma age is appropriate for eruption from Tomóchic caldera, it was discounted by Swanson (1977) as relatively insignificant and also by Wark et al. (1990), who considered it correlative with the Cascade tuff, which was believed to have erupted from the Ocampo caldera centered 30 km west (Swanson, 1977; Bockoven, 1980). Kempter (1986), however, noted that although poorly welded, the Cueva tuff could be considered a significant ignimbrite by virtue of its thickness and widespread distribution. The Cueva tuff, in fact, may exist in the Copper Canyon area, but we have not attempted to distinguish Cueva tuff from among this area’s many similar-looking, punky, stratigraphically high ignimbrites.

The Heredia tuff could also probably be considered a candidate for eruption from the Tomóchic caldera, and our study of the Copper Canyon area reveals a number of other units of appropriate age. The Divisadero tuff, for example (ca. 30 Ma), also corresponds well with ages from within the Tomóchic caldera. The Divisadero tuff is far from being a minor unit, and its high stratigraphic position fits well with the relatively pristine condition of the Tomóchic caldera. It is also interesting that the Divisadero tuff is so strikingly similar in appearance and mineralogy to the Vista tuff, the first ignimbrite that erupted from the Tomóchic volcanic center. A major drawback is that the nearest known exposure of Divisadero tuff is at San Juanito, 25 km southeast of the Tomóchic caldera. While the solution to this problem will fall to future workers, we can at least eliminate those ignimbrite units erupted from other calderas sources. The following section describes the well-preserved Manzanita and San Juanito calderas and discusses stratigraphic evidence indicating a Copper Canyon caldera and hinting at yet another in El Sierra Comanche.

San Juanito Caldera

The existence of a resurgent caldera centered on Cordon Cumbre Alta, 15 km northwest of San Juanito (Figs. 5 and 8), the town from which the caldera takes its name, had been suspected from earlier remote-sensing observations and reconnaissance work (see Swanson and Wark, 1988). This study confirms those observations. The caldera’s resurgent dome forms the continental divide in this part of the Sierra Madre Occidental, and precipitation there nourishes three major river systems (Fig. 2). Rio Tomóchic drains the caldera’s northern moat, flows northward through the moat of the Tomóchic caldera, then follows a torturous path westward to discharge into the Gulf of California as the Rio Yaqui. Streams draining the caldera’s southern side feed into the Rio Conchos and ultimately discharge into the Gulf of Mexico via the Rio Grande. The caldera’s western moat is drained by the Rio Oteros, which ultimately joins water flowing from Copper Canyon’s Rio Urique to flow into the Gulf of California as the Rio Fuerte.

The central dome of the San Juanito caldera rises to an elevation of 2860 m above sea level and is composed mostly of lithic-rich ignimbrite, the base of which is not exposed (Fig. 5). The rock contains ~20% phenocrysts of plagioclase and altered biotite set in a groundmass of reddish-brown shards, which have been twisted and contorted by an abundance of included rock fragments. Lithic fragments up to 6 m in length are noted, and they appear to increase in size and abundance toward the caldera’s margin. The intracaldera tuff is locally overlain along the dome’s crest and flanks by lava-flow rock, generally of intermediate composition (Fig. 5).

The northern half of the caldera’s resurgent dome is surrounded by the typical moat lithologies of sedimentary rock and poorly indurated tuff. The southern flank of the resurgent dome is overlain by Mogotabo’s unit 3 and the Quemada tuff, which dip gently away from the central dome. Typical moat lithologies, therefore, are not exposed around the southern half of the caldera, making the position of the caldera’s southern margin somewhat speculative. The caldera’s topographic margin is well displayed around the northern side of the caldera, where moat sedimentary rocks adjoin older ignimbrite and intermediate lava of the caldera’s topographic rim (Fig. 5). A caldera, ~20 km in diameter, is suggested by a projection of the caldera’s rim, but complexities and uncertainties remain because the southern part of the caldera is covered by younger ignimbrites.

Because petrographic differences imposed by differences in depositional settings between intracaldera and outflow ignimbrites can be significant, we place particular emphasis on phenocryst mineralogy and shard characteristics in making our correlations. Of the various area units, the San Juanito’s intracaldera tuff most closely
Figure 8. Photo composites of the San Juanito and Manzanita calderas.
resembles Mogotabo unit 3 and the San Felipe tuff. Mogotabo unit 3, however, is interpreted to lie within San Juanito caldera’s moat. The San Felipe tuff, dated at 36.5 Ma (Wark et al., 1990), is the oldest ignimbrite exposed along the topographic rim of the Tomóchic caldera. At Tomóchic, it consists of three, thick, similar-looking cooling units that thicken considerably in the direction of the San Juanito caldera and that match that caldera’s intracaldera ignimbrite in terms of phenocryst mineralogy. A felsic flow-dome lava exposed across the San Juanito caldera’s western margin (Fig. 5) was sampled for age determination in the hope that its age might strictly constrain both the caldera’s age and erupted units. An age of ca. 36.5 Ma, for example, would have strongly supported the San Juanito caldera as the source for the San Felipe tuff. While the rock sampled is in a structural position appropriate for ring-fracture volcanism, the lava exposures do not extend for any great distance around the caldera margin but do continue for many kilometers southwest of the caldera (Fig. 5). Also, similar-looking felsic flows east of the caldera appear to extend across the caldera boundary to where they overlie mafic lava known to be post-Disisadero in age (Fig. 5). While the age of 29.4 Ma (Table 1) provides a minimum age for San Juanito caldera formation, the petrographic similarity of the intracaldera tuff to the 36.6 Ma San Felipe tuff argues for a significantly older age.

Manzanita Caldera

The Manzanita caldera, unlike those at Tomóchic and San Juanito, is not obvious on space photos or imagery. Its presence was suspected by the arcuate geometry of area streams as seen on topographic maps and by the massive, monolithic appearance of the Sierra Manzanita (Fig. 8). It was confirmed as a caldera when geologic mapping showed the Sierra Manzanita to consist of over 400 m of very lithic-rich ignimbrite (base not exposed) surrounded by typical moat lithologies.

The intracaldera ignimbrite exposed in the resurgent dome contains ~5%–10% phenocrysts of plagioclase and biotite set in a groundmass of large, clear, chaotically foliated shards and pumice. Lithic fragments, typically rhyolite lava, are found in abundance, and they range in size from microscopic fragments to megablocks many tens of meters in diameter. The abundance of fragments produces a chaotic orientation of shards, as seen at the thin section level. In the field, eutaxitic foliation is locally seen to wrap in all directions around included, building-size lithic fragments. The intracaldera tuff of the Manzanita is correlated with the Quemada tuff (Mogotabo unit 5). Outflow exposures of this unit throughout the study area share the same low crystal content, phenocryst mineralogy, and general appearance in terms of color,ash, and pumice characteristics, but they lack the abundant lithic fragments.

The caldera’s resurgent dome is overlain and nearly surrounded by the typical moat lithologies of sedimentary and poorly indurated volcanic rocks (Figs. 6 and 8). Lavas of intermediate to silicic composition, however, dominate in the southern moat (Fig. 6). The Copper Canyon highway passes between the Sierras Manzanita and El Comanche (Figs. 2 and 6), and from Arroyo Ancho to Rancho Blanco, it traverses the Manzanita caldera’s western moat. The Manzanita caldera’s topographic rim can be traced in an unbroken arc west of the highway as it cuts the eastern flank of Sierra El Comanche. Also, Manzanita moat sedimentary rock contains clasts of Comanche tuff, indicating that the Manzanita caldera and the Quemada tuff postdate the Comanche tuff and any potential caldera immediately to the west. Viewed from the Sierra El Comanche, the Manzanita caldera’s central dome gives the appearance of being buried to a relatively high level by moat sedimentary and volcanic rocks (Fig. 8). Based upon known rim-to-dome distances and reconnaissance mapping, the Manzanita caldera appears to be a relatively modest 15 km in diameter, but only its western rim has been located.

Copper Canyon Caldera

A 1-km-thick ignimbrite (base not exposed) constitutes the lower two-thirds of the exposed stratigraphic section at Disisadero. While this extraordinary thickness certainly suggests accumulation within a caldera, very little else is known about the proposed structure, and we can discern no physiographic expression of a Copper Canyon caldera on space images. The Copper Canyon tuff, as viewed from Disisadero, appears to extend in a fairly horizontal manner over great distances across the canyon and upriver. Rock layers a few kilometers downstream from Disisadero, however, are seen to dip steeply in a downstream direction. It is not known if this might represent the southern flank of a resurgent dome or if they are caused by some other structural control. North of Disisadero, the various volcanic units above the Copper Canyon tuff do dip gently eastward away from the Copper Canyon highway (Fig. 4), becoming approximately horizontal near the Rio Urique, and then they rise slightly further to the east. The Rio Urique may have followed the axis of this syncline prior to cutting into the hard, vertically jointed Copper Canyon tuff. More work, however, will be needed to determine if the syncline is related to an underlying caldera structure, perhaps as a moat-filling sequence. Disisadero tuff cooling units exposed along the highway between Pitorreal and Creel (Fig. 4) increase drastically and abruptly in thickness in the direction of Copper Canyon. Again, it is tempting to call upon an underlying structural control. This limited stratigraphic information suggests that Copper Canyon exposes the thick, intracaldera facies of a caldera that has served as a trap for subsequent volcanism, allowing the local preservation of one of the region’s best stratigraphic sections.

A Manzanita Caldera?

The central part of the Sierra El Comanche contains a great thickness of ignimbrite of plagioclase-pyroxene mineralogy overlain in places by hundreds of meters of intermediate lava rock (Fig. 6). Reconnaissance traverses along flanks of the range encounter lava and sedimentary layers, typical of moat lithologies, dipping radially outward from the core of the Sierra El Comanche. Although extremely thick, a basal vitrophyre of El Comanche tuff can be observed, something unexpected of an intracaldera ignimbrite. Still, cooling breaks with vitric horizons have been described from other intracaldera tuffs, as in the San Juan volcanic field’s Bachelor caldera, where vitrophyric zones occur adjacent to caldera-collapse breccias (Lipman, 2000). The known distribution of presumed resurgent dome and moat lithologies suggests a caldera of ~25 km in diameter. Because the circular form of the adjacent Manzanita caldera moat cuts into Sierra El Comanche, and blocks of Comanche tuff are found in its moat sedimentary rock, the Comanche tuff and any related caldera must predate formation of the Manzanita caldera.

SUMMARY AND DISCUSSION

The Copper Canyon Area

Copper Canyon and the Mogotabo section at the southern limit of the map near Disisadero is interpreted as exposing an intracaldera ignimbrite from a caldera that subsequently served as a trap for five younger ignimbrites from other sources. The concordant nature of the units, the preservation of unwelded tops, the general lack of interlayered sedimentary beds, and the available age information suggest rapid emplacement relatively late in the volcanic history of the region. The Mogotabo section is capped by the Disisadero tuff, which laterally forms a widespread ignimbrite cap across much of the southern and central map sections, as well as the southern limit of the map near Divisadero.
as throughout the upper Rio Urique and Rio Conchos drainage systems. The Vista and Rio Verde tuffs, previously known from Tomólíchic, are exposed in the central part of the map area, unconformably below the Divisadero tuff. The central section also contains the San Juanito caldera, the southern moat of which is buried by some units exposed in the Mogotabo section. Lava exposed across the San Juanito caldera’s western rim returned an age of 29.4 Ma, but the structure’s intracaldera ignimbrite resembles the 36.5 Ma San Felipe tuff, known from exposures north of the caldera and at Tomólíchic. The northern map area contains the Manzanita caldera, source for the Quebrada tuff. The Quebrada tuff is one of the units that flowed into the San Juanito caldera, and it crops out at Copper Canyon as Mogotabo unit 5. A pre-Manzanita caldera may exist in the Sierra El Comanche, where units similar to Mogotabo units 2 and 4 are exposed.

The Copper Canyon–Tomólíchic Region

The region’s oldest known ignimbrites are the Cascabel and San Felipe tuffs (Table 2) described from the Tomólíchic area and dated at 38.2 and 36.5 Ma (Wark et al., 1990). The source for the Cascabel is unknown, but our study suggests the San Juanito caldera as the source for the San Felipe tuff. If so, known regional caldera activity then shifted from San Juanito (36.5 Ma), northward to the Tomólíchic volcanic complex, where the Vista tuff was erupted at 34.1 Ma during formation of the Las Varas caldera (Fig. 2). Although Tomólíchic ultimately experienced a second major eruption during formation of the Tomólíchic caldera, the ca. 30 Ma ages on rocks so closely related to the Tomólíchic cycle (see Wark et al., 1990) cast doubt on the caldera as the source for the Rio Verde tuff. Alternatively, a number of ignimbrite formations of more appropriate age, e.g., Cueva, Heredia, Divisadero, and Mogotabo unit 3, and without recognized source calderas are now known. Tomólíchic is the region’s most obvious caldera with a pristine condition, which is also more consistent with it being the source for one of the region’s younger units.

Following activity at San Juanito (36.5 Ma) and at Las Varas (34.1 Ma), a tentative sequence for caldera formation consistent with stratigraphic relationships across the Copper Canyon area would be the formation of the Copper Canyon caldera, the proposed Sierra Comanche calderas, the Manzanita, and the Tomólíchic calderas. The emplacement of ignimbrites from these major sources, together with the eruption of interlayered units from sources yet unknown, would have provided a ca. 30 Ma, rapid-fire climax to caldera-related volcanism in the region.

Discussion

In a review of calderas of the Sierra Madre Occidental, Swanson and McDowell (1984) called attention to the general similarities between the well-known San Juan volcanic field and volcanic rocks of the Sierra Madre Occidental. Volcanism in both areas was noted to have progressed from dominantly intermediate, stratovolcano-related eruptions to dominantly silicic volcanism of the “great ignimbrite flare-up.” The view provided by the combined Tomólíchic–Copper Canyon area into the heart of the Sierra Madre Occidental volcanic field extends those earlier comparisons to the core of each volcanic field.

Lipman (2000) reported that exposures of early stratovolcano-related rock (Conejos Formation) in the central San Juan volcanic field are rare and occur mostly as surviving pre-ignimbrite topographic highs exposed along caldera walls. Similarly, we have yet to identify any pre-ignimbrite volcanic sequence in the Copper Canyon–Tomólíchic region, although a thinner cover exposes Laramide-age plutonic and volcanic rocks in Batopilas canyon to the south (Bagby, 1979). Lipman (2000) reported that intermediate-composition volcanism continued during the period of ignimbrite eruption and caldera formation. Andesitic volcanism in the Copper Canyon–Tomólíchic region predates and postdates caldera formation at the Tomólíchic volcanic complex, the San Juanito caldera, the Manzanita caldera, as well as ignimbrite in the Sierra El Comanche. Andesitic lavas, therefore, are found throughout the ignimbrite stratigraphic sections in core regions of both the Copper Canyon and San Juan volcanic fields, suggesting that intermediate-composition magmas played a role in the ignimbrite genesis for both regions (Wark, 1991; Lipman, 2000).

The silicic components of both volcanic fields thicken from a fringe populated by isolated sources (see Swanson and McDowell, 1984; Lipman, 2000) to a central core consisting of an extremely thick ignimbrite section erupted from a cluster of overlapping calderas. Nine major ignimbrites and seven exposed calderas are known from the core of the San Juan volcanic field, and six successive stacked calderas are indicated for the Creede caldera area, representing a potential cumulative subsidence exceeding 15 km (Lipman, 2000). Incomplete though it is, the image emerging from the Copper Canyon–Tomólíchic region is similar to that of the central San Juan volcanic field, where repeated, overlapping caldera-forming volcanism has produced a region where virtually every area may ultimately be found to contain at least one caldera and in which an abnormally thick, stratigraphically complex silicic volcanic section is the rule. While recurrent stoping and assimilation from below combined with resurgent uplift and erosion from above would have prevented the total core-area ignimbrite thickness from approaching total subsidence, clearly the commonly reported 1 km average ignimbrite section thickness for Sierra ignimbrites does not apply to the core of the volcanic field and will have to be adjusted upward, as will estimates of total Sierra ignimbrite volume.

With the San Juan volcanic field as a reference standard, Swanson and McDowell (1984) estimated that the volume of the Sierra Madre volcanic field might require 350 calderas. It might be surprising then that so few are “glaringly obvious” on space photographs and images. Similar observations have been used to support the hypothesis that fissure-vent eruptions related to episodes of Basin and Range faulting are the dominant source for Sierra Madre Occidental ignimbrites (Aguirre-Díaz and Labarthe-Hernández, 2003). Our field investigations show, however, that ignimbrite volcanism was most active in that part of the volcanic field least affected by extensional faulting, that complete and fragmented calderas occur in abundance in the Tomólíchic-Copper Canyon region, that these calderas generally conform to the resurgence caldera model that has evolved since the seminal work of Smith and Bailey (1968), and that similar calderas and caldera complexes can be expected throughout the core of the Sierra Madre Occidental.

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