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GEOLOGY OF THE DONA ANA MOUNTAINS, SOUTH-CENTRAL NEW MEXICO: A SUMMARY

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Abstract—Located a few kilometers north of Las Cruces in south-central New Mexico, the Dona Ana Mountains are part of a late Tertiary fault block that extends from the northern Franklin Mountains to San Diego Mountain. Uplift along the Jornada fault on its eastern side and subsidence along the Robledo fault into the northern Mesilla half graben has resulted in a ~15° westward tilt of the Dona Ana block. Early Pliocene to Quaternary axial-fluvial and piedmont-slope deposits, paleocanyon fill, and pediment veneers onlap bedrock around the perimeter of the range. Two easterly trending, dike-filled faults or fracture zones, both downthrown to the south, divide the range into three structural blocks. The northern, structurally highest block primarily consists of easterly trending, folded and thrust-faulted upper Pennsylvanian and Lower Permian sedimentary rocks, deformed during the latest Cretaceous-early Tertiary Laramide orogeny. The Permo-Pennsylvanian strata are intruded by the Summerford Mountain syenite sill. The central block exposes a thick sequence of southerly dipping, upper Eocene andesite and dacite lava flows and volcaniclastic rocks assigned to the Palm Park Formation. Deeply eroded remnants of the Dona Ana caldera constitute the structurally lowest, southern block. Eruption of the ~36 Ma Dona Ana Rhyolite, an ash-flow tuff sequence at least 440 m thick, triggered caldera collapse. Post-caldera fallout tuffs and ash-flow tuffs hundreds of meters thick accumulated within the caldera, most notably in the Red Hills graben, where chaotic megabreccia, rhyolite flows, and rhyolite dome-flow complexes and other intrusives were emplaced. Rhyolite and syenite sheets or dikes were emplaced along the northern margin of the caldera, as well as along faults that earlier had broken both caldera tuffs and post-caldera rocks. The Summerford Mountain sill may have extended below both the northern and central blocks, as well as beneath the Dona Ana caldera, where it may have been the source of felsite to syenite dikes at the northern margin of and within the caldera. Because it is buried by younger rocks or alluvium, the western, southern, and eastern limits of the caldera are unknown. However, the western boundary may have been hinged rather than broken, as suggested by the gradual westward decrease in the number and thickness of dikes along the northern margin of the caldera.

INTRODUCTION

Located a few kilometers north of Las Cruces (Fig. 1), the Dona Ana Mountains are a relatively small, but rugged desert mountain range with bedrock outcrops exposed over an area of approximately 130 km^2. Dona Ana Peak, the highest point in the range at somewhat more than 1770 m above sea level, is approximately 580 m higher than the floodplain of the Rio Grande, which skirts the western edge of the range. Viewed from Las Cruces, the most conspicuous part of the range is its south-facing escarpment, which includes Dona Ana Peak. Less apparent from the city is its bold, east-facing escarpment along the eastern slopes of the range, as well as the prominent peak of Summerford Mountain at its northeastern corner. Broad, pedimented surfaces extend eastward and southward from the escarpments and nearly surround Summerford Mountain. Interior and western parts of the mountains are rather intricately eroded, primarily by seven arroyo systems, which head in the eastern part of the range, then flow westward in incised, but somewhat shallow canyons to the Rio Grande. Outcrops throughout the range are locally barren of vegetation, elsewhere only slightly obscured by scattered juniper trees and vegetation typical of northern parts of the Chihuahua desert.

Although the map of New Mexico by Darton (1928) portrayed the general geology of the Dona Ana Mountains, F.E. Kottlowski was the first to map the range in detail during the

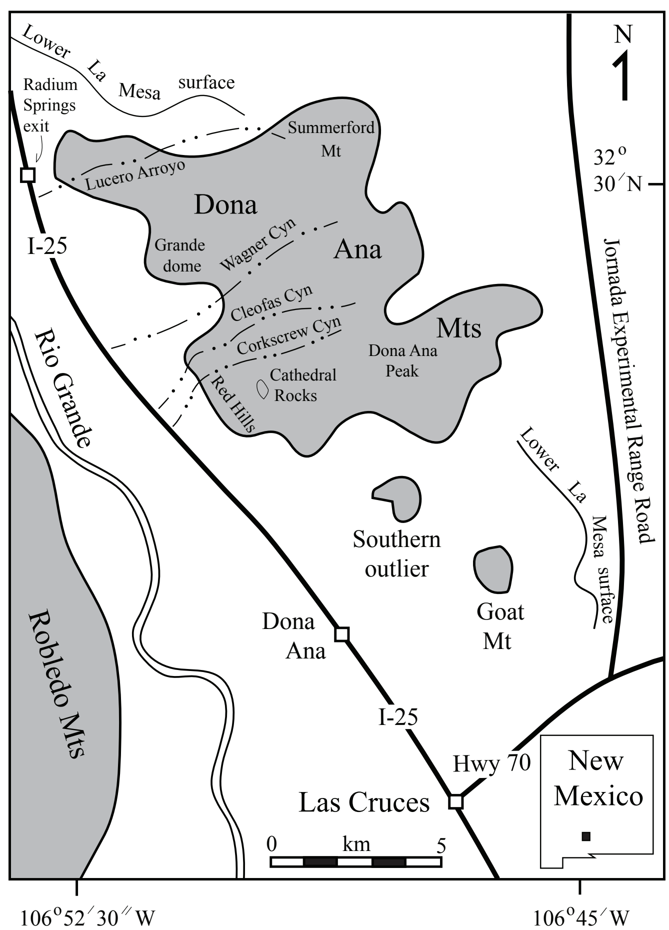

FIGURE 1. Location of Dona Ana Mountains and adjacent part of Robledo Mountains, south-central New Mexico.

1950s. Kottlowski's 1960 map was incorporated into the map and report published by the New Mexico Bureau of Mines and Mineral Resources in Circular 147 (Seager et al., 1976). Because the 1976 map was compiled on a somewhat inaccurate planimetric base, W.R. Seager remapped the range in 2016, placing the geology on a modern topographic base and reevaluating some of the geologic relationships. Studies of Paleozoic, middle Tertiary, and upper Tertiary to Quaternary rocks began in the 1990s and continue to the present day (Goerger, 1993; Haga, 1994; Mack, 2007; Mack and James, 1992; Mack et al., 1993, 1994a, b, c, 1996, 2003, 2009, 2010, 2013; Durr, 2010; Stautberg, 2013; Harder, 2016; Creitz et al., this volume; Ramos and Heizler, this volume).

REGIONAL SETTING

The Dona Ana Mountains are the largest of several exposed segments of a major fault block that extends northward from the northern Franklin Mountains to the northern tip of San Diego Mountain (Fig. 2). Throughout much of its length, the fault block is buried beneath latest Tertiary and Quaternary sedimentary rocks and unconsolidated sediment. The Bishop Cap Hills, Tortugas ("A") Mountain, and San Diego Mountain are somewhat smaller exposures of bedrock along the length of the uplift (Seager et al., 1987). Shallow water wells have penetrated the buried fault block in parts of eastern Las Cruces (Seager et al., 1987).

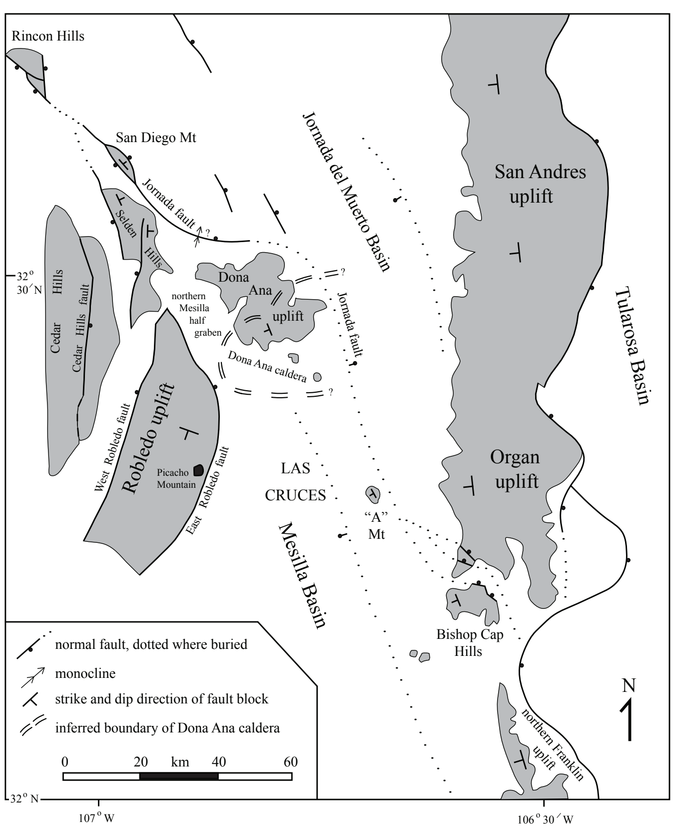

FIGURE 2. Regional tectonic map of south-central New Mexico in the vicinity of Las Cruces, adapted from Seager et al. (1987).

Throughout its length, the fault block is bordered on its eastern side by the Jornada fault, a major late Tertiary normal fault that is downthrown to the east (Fig. 2). The southern part of the fault block, including the Dona Ana Mountains, is tilted westward ten to fifteen degrees. At the northern edge of the Dona Ana Mountains, however, the Jornada fault bends abruptly westward and links to the north with the fault on the east side of San Diego Mountain (Fig. 2). East of the Dona Ana Mountains is the southern Jornada del Muerto Basin, a late Tertiary half graben or asymmetric graben that may contain several thousand meters of basin fill (Seager et al., 1987).

The down-dip part of the Dona Ana Mountains segment of the fault block forms the west-tilted northern Mesilla half graben (Fig. 2). The western boundary of the half graben is the East Robledo fault, which, like the Jornada fault, is downthrown toward the east. The Robledo Mountains constitute the footwall of the northern Mesilla half graben (Fig. 2; Seager et al., 1987, 2008). Although the Dona Ana Mountains are now deeply eroded, the general westward tilt of the range can be viewed from many places in Las Cruces, in that the range gradually becomes lower in elevation westward.

The Rio Grande flows along the western edge of the northern Mesilla Valley, probably in response to repeated movement along the East Robledo fault and consequent westward tilt of the basin floor in latest Tertiary and Quaternary time (Mack and Seager, 1990). However, the northern Mesilla half graben is notably shallow, as indicated by bedrock outcrops extending from the Dona Ana Mountains to the modern Rio Grande floodplain (Seager et al., 1976). In addition, hanging wall-derived, alluvial-fan sediment ranging in age from Pliocene to Holocene nowhere exceed 100 m in thickness, and older Tertiary rift-fill sedimentary rocks are missing in the northern part of the basin, although slivers of presumably Miocene pebble and granule conglomerate are present along the East Robledo fault in the east-central part of the range (Seager et al., 2008).

The Jornada and East Robledo faults were initiated at different times in the history of the southern Rio Grande rift. Seager et al. (1984) and Mack et al. (1994c) suggested that the Robledo uplift was initiated late in the history of the rift, sometime after 9.6 Ma. This idea is based on the absence of local clasts derived from the Robledo Mountains in adjacent upper Miocene alluvial-fan conglomerate, within which the 9.6 Ma Selden Basalt is interbedded. The previously described thin basin fill in the northern Mesilla half graben also supports the idea of late development of the East Robledo fault. In contrast, provenance and paleocurrent data from the middle to upper Miocene Rincon Valley Formation suggest that the uppermost Eocene Dona Ana Rhyolite, the syn-collapse ash-flow tuff of the Dona Ana caldera in the Dona Ana Mountains, was supplying sediment to the southeastern part of the ancestral Palomas Basin, located to the west and northwest of the Dona Ana Mountains (Mack et al., 1994c). This implies that by middle Miocene time, the Jornada fault had uplifted the Dona Ana Mountains to a level in which deep-seated rocks of the Dona Ana caldera were exposed. Moreover, the wide and deeply eroded pediments and paleocanyons within and along the eastern and southern flanks of the Dona Ana Mountains suggest a long period of uplift and erosion prior to Pliocene time. Finally, the presumably thick basin-fill sequence in the southern Jornada del Muerto half graben/graben is consistent with early (middle Miocene) and prolonged movements on the Jornada fault.

It is also possible to deduce the more recent history of activity on the Jornada and East Robledo faults. Scarps and offset of lower to upper Pleistocene deposits along the East Robledo fault indicate repeated episodes of fault movement in the past ~0.8 Ma, even within the last 100,000 years (Seager et al., 2008). Recent earthquakes beneath the Mesilla Valley (magnitude 2.5–3.0) are possibly related to movement on this fault. In contrast, long segments of the Jornada fault lack scarps entirely and seemingly have been inactive throughout the Quaternary. Movement on the northernmost segment of the fault, however, has deformed or offset the 0.8 Ma La Mesa geomorphic surface by at least 50 m, although the precise number and timing of Quaternary fault ruptures have not been determined.

BASIN-FILL DEPOSITS

Pliocene and Quaternary sediments and sedimentary rocks have buried bedrock pediments around the entire perimeter of the Dona Ana Mountains. These undeformed strata fall into two groups: older Camp Rice Formation and younger inset valley fill. Camp Rice strata range in age from early Pliocene (~5 Ma) to early Pleistocene (~0.8 Ma; Mack et al., 1993, 1996, 1998). Mack et al. (2009) compiled a composite section ~100 m thick of the Camp Rice Formation that onlapped the northwestern part of the Dona Ana Mountains. Adjacent to the northeastern Robledo Mountains, ~130 m of Camp Rice is present, although the base is not exposed (Mack et al, 1993).

The Camp Rice Formation consists of two mappable facies: piedmont slope and axial fluvial (Seager et al., 1987; Mack and Seager, 1990). The piedmont-slope facies comprise conglomerate/gravel and coarse sand/sandstone deposited as alluvial fans, paleocanyon fill, and pediment veneers. Also included in the piedmont-slope facies are finer-grained sand/sandstone and mud/mudstone deposited on alluvial flats. The axial-fluvial facies documents the existence of an ancestral Rio Grande, which shifted across a wide area of south-central New Mexico (Mack et al., 2006). The axial-fluvial facies consists of granular and pebbly sand/sandstone deposited in fluvial channels, and finer sand/sandstone and mud/mudstone deposited on the floodplain (Perez-Arlucea et al., 2000). Many gravel-sized clasts in the axial-fluvial facies were derived from distant, upstream sources, although clasts from local sources are common as well. Two pumice-rich beds deposited by the ancestral Rio Grande are present adjacent to the northwestern Dona Ana Mountains. The older bed has pumice dated at ~3.1 Ma that was derived from the Mount Taylor volcanic field, whereas ~1.6 Ma pumice in the younger bed was derived from the Valles caldera (Mack et al., 2009). Calcic paleosols of stages II, III, and IV morphology are locally present within both the piedmont and axial-fluvial facies (Mack and James, 1992; Mack et al., 2006). The constructional top of the axial-fluvial facies is known as the La Mesa surface and is capped by meter-thick, stage IV or V petrocalcic paleosol (Gile et al., 1981). Erosional remnants of this surface are well exposed along the northern and southeastern margins of the Dona Ana Mountains.

Younger inset valley fill deposits generally are middle Pleistocene to Holocene in age and were deposited after the Rio Grande began entrenching itself into its modern valley at ~0.8 Ma. These deposits are generally inset against older strata of the Camp Rice Formation along the margins of the Rio Grande valley, but may overlap and bury older deposits on piedmont slopes in the Jornada del Muerto Basin. As in the Camp Rice Formation, two facies are recognized in the inset valley fill deposits. Piedmont-slope deposits are mostly gravel and sand deposited on alluvial fans, as pediment veneers, and as arroyo alluvium. Axial-fluvial deposits primarily consist of granular and pebbly sand of the modern Rio Grande floodplain, as well as older deposits that intertongue with or are inset against stranded alluvial-fan gravels located as much as 15 m above the modern floodplain. Several generations of valley fill are recognized and correspond to repeated episodes of valley entrenchment and partial backfilling during the last ~0.8 Ma (Gile et al., 1981). Both axial-fluvial and piedmont-slope deposits are 30 m or less in thickness, and older deposits may be capped by stage II, III, or IV calcic soils (Gile et al., 1981).

BEDROCK GEOLOGY

From a geologic perspective, the Dona Ana Mountains can be divided into three blocks separated by two northeasterly trending fault or fracture/intrusive zones (Fig. 3). Each block is distinguished by different suites and ages of rocks that record tectonic or volcanic events that took place at three different times in the history of this part of southern New Mexico.

Northern block

The northern block (Fig. 3) is characterized by folded Pennsylvanian and Permian sedimentary rocks and by the earliest Oligocene(?) Summerford Mountain sill. At the southern boundary of this block, the east-northeast-trending Wagner Canyon fault, downthrown to the south, truncates the Paleozoic strata and juxtaposes them against middle Tertiary volcanic rocks in the central block.

Upper Pennsylvanian and lowermost Permian strata are assigned to the Panther Seep Formation. Estimated to be at least 600 m thick, the base of the Panther Seep is not exposed and only partial sections have been logged (Seager et al., 1976; Goerger, 1993). It consists of interbedded poorly fossiliferous, often sandy limestone, stromatolitic limestone, dark gray, laminated micrite limestone, fine sandstone, siltstone, and dark gray shale (Seager et al., 1976; Goerger, 1993). A poorly exposed interval of gypsum also is present near the top of the formation along the northern limb of the Grande dome (Fig. 3). The rock types and stratigraphic position of the Panther Seep in the Dona Ana Mountains are similar to the Panther Seep in the southern San Andres Mountains (Kottlowski et al., 1956) and in the Organ Mountains (Seager, 1981). The Panther Seep in the Dona Ana Mountains is interpreted to have been deposited in the Orogrande Basin (Seager et al., 1976), primarily because

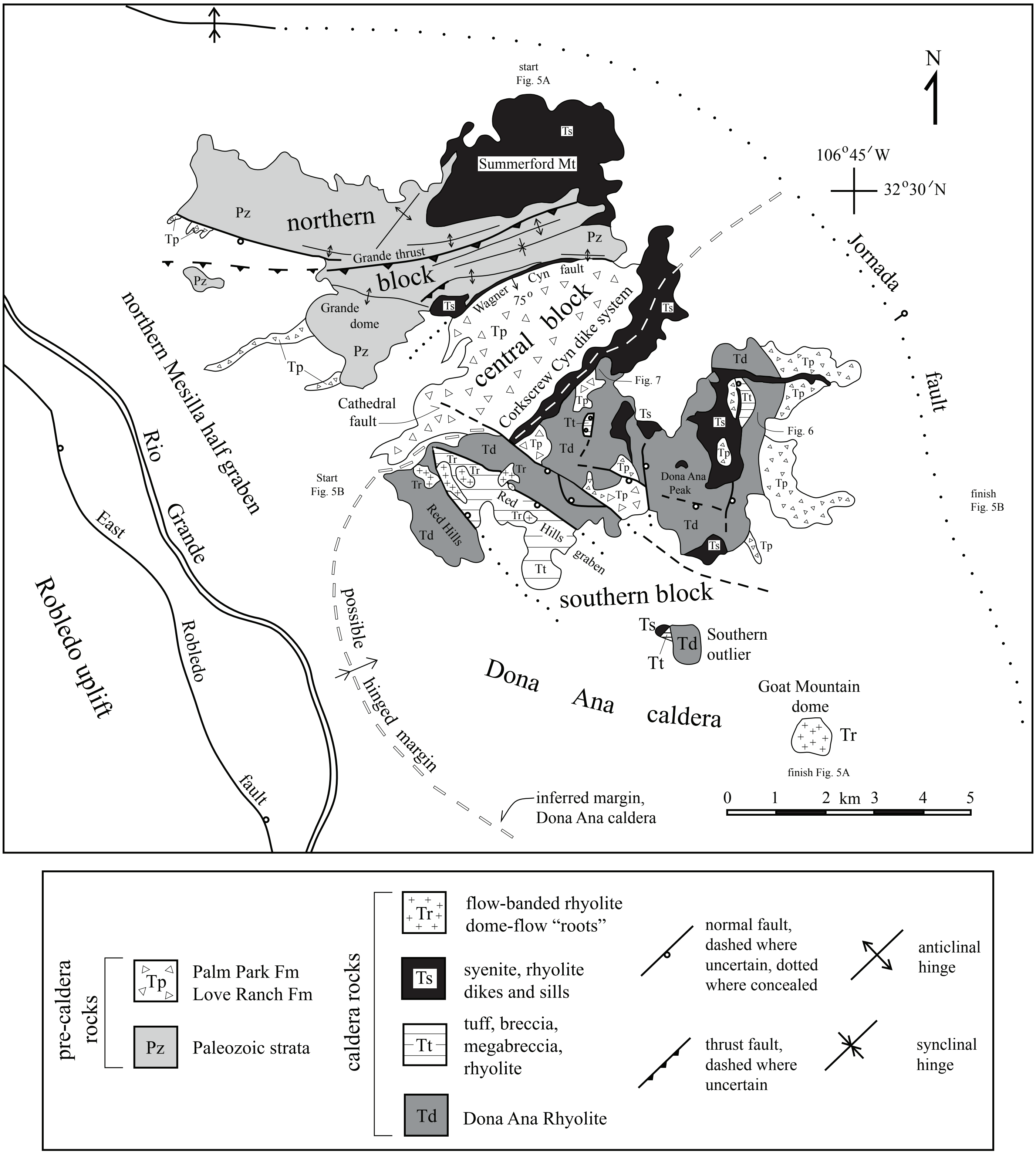

FIGURE 3. Generalized geologic map of the Dona Ana Mountains, adapted from Seager et al. (1976) and Seager et al. (1987).

it is ~80% thicker and has a greater relative abundance of sand, silt, and clay than coeval, primarily shallow-marine limestones in the Robledo Mountains that were deposited on the Robledo Shelf (Kottlowski, 1963; Goerger, 1993; Seager et al, 2008). This suggests that the Orogrande Basin subsided at a greater rate and was a locus for influx of siliciclastic sediment compared to the Robledo Shelf.

The remainder of Lower Permian strata in the northern block of the Dona Ana Mountains is assigned to the Hueco Formation and overlying Abo Formation, which correlate to the lower three members of the Hueco Formation in the Robledo Mountains (Fig. 4; Seager et al., 1976; Seager et al., 2008). The fine-scale interbedding of facies in these strata cannot be shown here. Instead, the strata are arranged into facies assemblages, although a few single intervals of marine shale, sandstone, and limestone are also shown (Fig. 4).

At Grande dome in the Dona Ana Mountains, the Hueco Formation is similar to the lower two members of the Hueco Formation in the Robledo Mountains (Figs. 3, 4; Seager et al., 2008). In both ranges, the lower part of the lower member of the Hueco, which is ~140 m thick in the Robledo Mountains, is dominated by cliff-forming, gray, cherty, fossiliferous, shallow-marine limestone, with a few beds of ooid limestone and limestone composed almost exclusively of pelmatazoan columnals. In addition, the lower part of the lower Hueco in the Robledo Mountains has a phylloid algae bioherm up to 6 m thick, whereas there are three tabular phylloid algae beds 1 to 4.5 m thick at Grande dome. In addition, a few beds of stromatolite-bearing, yellow-tan dolostone, which were probably deposited in lagoon to supratidal environments, are present in both ranges. Also present in the east-central Robledo Mountains, but absent at Grande dome are two intervals 3 and 10 m thick of sandstone, crossbedded pebbly, sandstone, and variable amounts of limestone and shale interpreted by Stautberg (2013) to represent estuarine deposits.

The lower part of the Hueco Formation also is exposed in the Dona Ana Mountains south of Summerford Mountain and north of the Wagner Canyon fault (Fig. 3). Although this area is structurally complex and the strata are locally contact metamorphosed, the lower part of the lower Hueco consists of cliff-forming, thick-bedded to massive limestones that are similar in appearance to the lower part of the lower Hueco member in the Robledo Mountains and at Grande dome. If these strata represent similar environments at all three locations, then the boundary between the Robledo Shelf and Orogrande Basin during deposition of the lower part of the lower Hueco would have been located east of the northern Dona Ana Mountains.

The upper part of the lower Hueco member and lower part of the middle Hueco member also are similar in the east-central Robledo Mountains and at Grande dome (Fig. 4). Ninety-six meters thick in the Robledo Mountains, this interval primarily consists of interbedded gray, marine shale, and yellow-tan, fine-grained dolostone interpreted to have been deposited in lagoon to supratidal environments (Mack et al., 2013). Also present are laterally discontinuous beds of crossbedded intraclast limestone that were deposited in tidal channels (Mack et al., 2013). Less common in this interval are beds of gray, fossiliferous, shallow-marine limestone.

The upper part of the middle Hueco member in the east-central Robledo Mountains is 50 m thick and is divisible into two intervals, which in ascending order are: 14 m of cliff-forming, gray, fossiliferous, shallow-marine limestone, and 36 m of interbedded fossiliferous, shallow-marine limestone, gray, marine shale, and yellow-tan, lagoon-to-supratidal dolostone (Fig. 4; Harder, 2016). A similar interval of the middle Hueco is present at Grande dome, but has not been logged in detail. In both ranges, the middle Hueco is conformably overlain

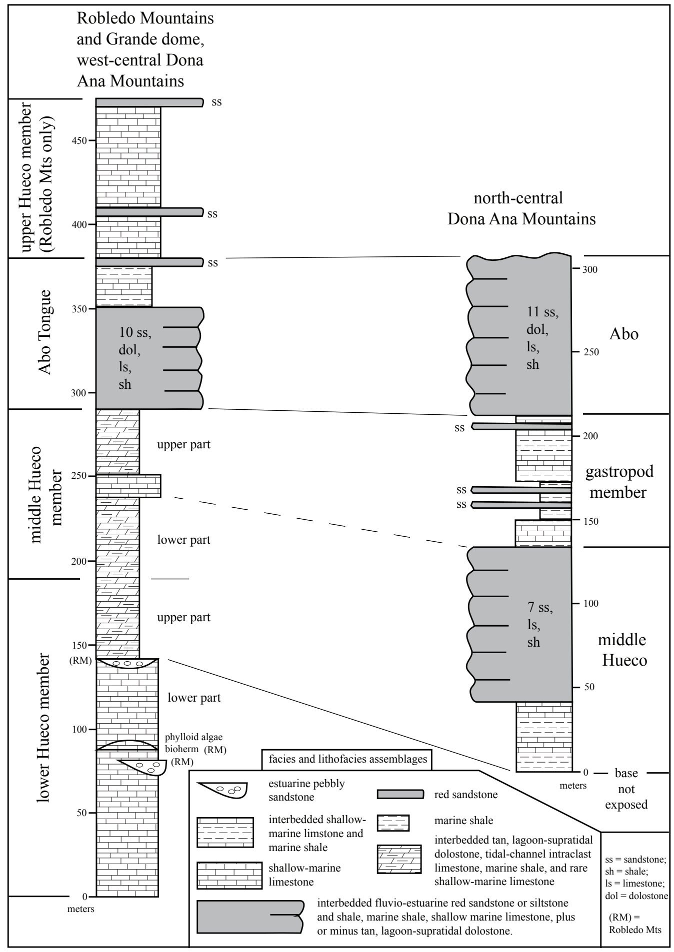

FIGURE 4. Lower Permian stratigraphy and facies assemblages of the Hueco Formation in the Robledo Mountains and Grande dome of west-central Dona Ana Mountains, and of the middle Hueco member, gastropod member of the Hueco, and the Abo Formation in the north-central Dona Ana Mountains, adapted from Mack (2007), Durr (2010), Mack et al. (2013), Stautberg (2013), and Harder (2106).

by the Abo. The abundance of shallow-marine limestone, the presence of lagoon-to-supratidal dolostone, and the paucity of sand suggest that the upper part of the lower Hueco and middle Hueco in the Robledo Mountains and at Grande dome were deposited on the Robledo Shelf.

In the north-central Dona Ana Mountains, just west of Summerford Mountain, a thick interval of Hueco Formation is exposed beneath the Abo Formation (Figs. 3, 4). In this area, Seager et al. (1976) originally subdivided the Hueco into the upper gastropod member and the lower "basin facies". In his more recent geologic map, W.R. Seager continued to use the gastropod member for the upper strata, but assigned the strata beneath the gastropod member to the middle Hueco member. The gastropod member probably correlates to the upper part of the middle Hueco in the Robledo Mountains and at Grande dome, whereas the middle Hueco member in the north-central Dona Ana Mountains probably correlates to the lower part of the middle Hueco and to some or all of the upper part of the lower Hueco in the Robledo Mountains and at Grande dome (Fig. 4). In the north-central Dona Ana Mountains, Durr (2010) measured 128 m of the middle Hueco member, but the base was not exposed, whereas Harder (2016) measured 94 m of gastropod member.

The middle Hueco and gastropod members in the north-central Dona Ana Mountains are significantly different in types and relative abundance of facies and facies assemblages compared to likely correlative strata in the Robledo Mountains and at Grande dome. Both members in the north-central Dona Ana Mountains are composed primarily of two facies assemblages: interbedded dark gray, marine shale and gray, fossiliferous limestone, with the relative abundance of limestone increasing upsection, and interbedded brown or red, fluvio-estuarine sandstone with or without a capping shale (10 sandstone intervals in middle Hueco member, 3 in gastropod member), dark gray marine shale, and gray, shallow marine limestone (Fig. 3; Durr, 2010). In addition, three, relatively thick intervals of dark gray, marine shale are interbedded with two beds of fluvio-estuarine sandstone near the middle of the gastropod member, and one bed of fluvio-estuarine sandstone is present within the marine shale-shallow-marine limestone facies assemblage near the top of the gastropod member (Fig. 4). Notably absent in the middle Hueco and gastropod members in the north-central Dona Ana Mountains are beds of yellow-tan, lagoon-to-supratidal dolostone. The abundance of siliciclastic sediment, particularly sandstone and thick, dark gray shale, and the absence of lagoon-to-supratidal dolostone in the middle Hueco and gastropod members in the north-central Dona Ana Mountains suggest that they were deposited in the Orogrande Basin, rather than on the Robledo Shelf.

The Abo Formation in the northwestern Dona Ana Mountains and the Abo Tongue of the Hueco Formation in the central Robledo Mountains are similar in terms of facies assemblages (Mack, 2007). In the Robledo Mountains, the Abo Tongue is 105 m thick and is conformably overlain by the upper Hueco member, whereas in the Dona Ana Mountains the Abo Formation is 90 m thick, but has an unconformable upper contact with the lower Tertiary Love Ranch Formation (Fig. 4). In both ranges, the most abundant facies assemblage in the Abo consists of interbedded red or brown, fluvio-estuarine sandstone or siltstone capped by estuarine shale, yellow-tan, lagoon-to-supratidal dolostone, dark gray, marine shale, and gray, shallow-marine limestone (Fig. 4; Mack et al., 2003; Mack, 2007). Some of the beds of estuarine shale that cap fluvio-estuarine sandstones or siltstones display vertic and calcic paleosols (Mack et al., 2010). Unique to the upper part of the Abo Tongue in the Robledo Mountains is a 25-m-thick, slope-forming interval of very fossiliferous marine shale and shallow-marine limestone that is overlain by a single interval of fluvio-estuarine sandstone (Fig. 4; Mack, 2007). Overall, the strong similarity between the Abo in both ranges suggest that depositional processes were the same across the region. Given the dominant facies assemblage and the criteria discussed above, however, it is difficult to assign the Abo to either the Orogrande Basin or to the Robledo Shelf. Perhaps the distinction between the basin and shelf no longer existed in this region by the time of Abo deposition.

Present only in the Robledo Mountains, the upper Hueco member is composed of cliff-forming interbeds of fossiliferous, shallow-marine limestone and at least two intervals of brown or red sandstone (Fig. 4).

The Pennsylvanian and Permian strata have been folded into a group of east-northeast-trending folds that verge northward (Fig. 3). From west to east the style of folding changes from a broad, open, asymmetric dome (Grande dome) to a pair of anticlines (northern and southern) separated by a deep syncline, the core of the latter packed with small, tight folds. The southern anticline is truncated by the Wagner Canyon fault. The steep to locally overturned northern limbs of the dome and the northern anticline are broken by the Grande thrust or reverse fault (Fig. 3). Easily traced for at least 6 km across the fold belt, the fault may extend under cover another 3 km or more westward to outcrops near the Rio Grande floodplain, where folded lower Hueco strata are structurally high above and to the south of adjacent Abo beds. That this deformation is related to the latest Cretaceous to early Tertiary Laramide orogeny is indicated not only by the style of folding and the northerly vergence of the folds (Seager, 2004), but also by the different depth of early Tertiary erosion in hanging wall and footwall blocks of the Grande thrust. Post-tectonic boulder conglomerates of the lower Tertiary Love Ranch Formation were deposited on Abo beds on the footwall block of the Grande thrust, but on more deeply eroded strata of the Hueco Formation on the hanging wall. The deformation probably occurred on the east-central part of the Rio Grande uplift, a large Laramide block that extended from the southern San Andres Mountains northwestward to the Black Range and possibly beyond (Seager et al., 1986, 1997).

Eastern outcrops of the folded Pennsylvanian and Permian strata are thermally metamorphosed and intruded by numerous dikes of felsite and syenite. Marble, porcellanitic shale, hornfels, metaquartzite, and metamorphic minerals such as epidote are common indicators of the metamorphism. The source of this metamorphism and the array of dikes is the Summerford Mountain sill, a coarse-grained syenite, which has yielded one whole-rock K/Ar age of 33.7 Ma (Seager et al., 1976). The sill dips southward at a relatively shallow angle beneath the folded Pennsylvanian and Permian strata, truncating them in the process. Many dikes in Paleozoic rocks can be traced into the sill, whereas others likely connect at depth. A trachyte porphyry dike within the Wagner Canyon fault, as well as a sheet of syenite in the Paleozoic rocks along the fault, were presumably fed from the sill beneath them. The sill may extend southward beneath both the central and southern blocks of the Dona Ana Mountains, sourcing numerous sheets and dikes in those blocks as well (Fig. 4).

Central block

The central block is bordered on the north by the Wagner Canyon fault and on the south by a wide zone of dikes and other latest Eocene-earliest Oligocene(?) intrusives named the Corkscrew Canyon dike system (Fig. 3). Outcropping rocks in the block consist almost entirely of intermediate-composition lava flows and lahar breccias and conglomerates assigned to the Palm Park Formation, which is correlative to the Orejon Andesite in the Organ Mountains (Dunham, 1935; Seager, 1981) and to the

Rubio Peak Formation in the southern Black Range and Cooks Range (Elston, 1956; Seager et al., 1982). New radioisotopic dates from the Palm Park Formation in the central block include U-Pb zircon ages of 42.0±0.6 and 41.0±0.65 Ma (Creitz et al., this volume), and a $^{40}Ar/^{39}Ar$ plagioclase age of 43.12±0.19 Ma (Ramos and Heizler, this volume). All three dates are from lava flows exposed in Cleofas Canyon in the southern part of the central block, and are probably from the upper part of the Palm Park Formation. Although a complete section has not been measured, the Palm Park in south-central New Mexico is estimated to be up to 610 m thick (Seager and Clemons, 1975), a number consistent with its estimated thickness in the central block of the Dona Ana Mountains. However, neither the base nor top of the Palm Park are exposed in the central block.

In the southern block, the top of the Palm Park Formation is marked by a discontinuous, thin (~30 m) series of basaltic andesite flows. In the northern block, boulder conglomerate beds of the Love Ranch Formation directly underlie or are interbedded with basal parts of the Palm Park. Locally, two or more lacustrine limestone beds are present in the lower part of the Palm Park in the northern block, and these are overlain by ~550 m or more of purple lahar breccias and conglomerates and volcaniclastic sandstones and conglomerates exposed in several canyons draining westward to the Rio Grande. No lava flows are present within these northwesternmost outcrops of the Palm Park Formation in the Dona Ana Mountains, a striking contrast with thick Palm Park lava flows exposed in the central and southern blocks.

In the central block, the Palm Park Formation consists primarily of massive, thick lava flows, some perhaps tens of meters thick, which dip consistently southward 10 to 12°. Thin, discontinuous lahar breccias and conglomerates are interbedded with the flows, strengthening the interpretation that the more abundant rocks are flows rather than intrusive bodies. Locally, steeply dipping flow banding is present, which may indicate the presence of small intrusives or may occur within lava flows. The lava flows are primarily porphyritic andesite and dacite, generally in shades of purple, grayish-purple, gray, or brownish-maroon. Phenocrysts are plagioclase and to a lesser extent hornblende. Alteration of plagioclase, mafic minerals, and groundmass is pervasive throughout the formation. Large parts of the outcrop belt are distinctly grayish-brown in color, probably as a result of oxidation of iron-bearing minerals. Lahar clasts are generally similar in mineralogy to the interbedded flows and display similar alteration. Some lahars are heterolithogic, whereas others are monolithologic. Lahars also may be interbedded with thin fallout ash beds or with beds of fluvial or hyperconcentrated-flow conglomerate.

It is tempting to suggest that Palm Park lavas accumulated on the slopes of a stratovolcano and that the lahars and volcaniclastic conglomerates and sandstones represent more distal, lowland deposits to the west. The thickness and widespread distribution of Palm Park lahar deposits and volcaniclastic conglomerates and sandstones west and northwest of the Dona Ana Mountains is consistent with this interpretation (Clemons, 1976; Seager and Mack, 2003; Seager et al., 2008). However, to the east and south of the range, Palm Park and equivalent rocks are either of limited exposure or buried, making the complete reconstruction of a late Eocene stratovolcano difficult.

Many dikes cut the Palm Park volcanic sequence. They are most numerous adjacent to the Corkscrew Canyon dike system, where they trend northeastward, parallel to the dike system. Thicker dikes are flow-banded rhyolite, whereas thinner dikes were mapped as felsite. A few dikes may be andesitic or trachytic in composition. Dike orientation becomes more scattered and dikes become thinner and less numerous away from the Corkscrew Canyon dike system.

Southern block

The southern block is the most complex of the three blocks, primarily because it exposes the partial remains of the upper Eocene Dona Ana caldera (Fig. 3; Seager et al., 1976). The northern boundary of this block, the Corkscrew Canyon dike system, is especially significant, because it is interpreted to also mark the northern structural margin of the caldera. Both the central and northern blocks are structurally high relative to the southern (caldera) block. They step down by faulting toward the caldera and are interpreted as being part of the rim and outer flank blocks of the caldera (Fig. 5A). In spite of the complexities within the southern block in general and within the caldera in particular, the southern block best reveals the westward tilt of the Dona Ana Mountains (Fig. 5B). Dips within the caldera fill are generally westward at low angles, although there are some exceptions, and deepest erosion of the caldera, into the pre-caldera Palm Park Formation, is along the eastern edge of the range. Uppermost parts of the caldera fill may be preserved along the western margin of the range, although exceptions exist. Thus, westward tilting of the Dona Ana fault block also tilted the older Dona Ana caldera westward as much as 15°.

Formation of the Dona Ana caldera apparently involved two stages. First, collapse of the caldera was initiated by eruption of the Dona Ana Rhyolite, a thick ash-flow tuff, whose outcrops are restricted to the southern block, south of the Corkscrew Canyon dike system. Second, post-caldera silicic eruptions at least locally buried the broken floor of the caldera, accumulating to notable thicknesses in grabens. Accompanying and following these post-caldera eruptions was the intrusion of dome/flow complexes, as well as syenite dikes and sheets into both caldera and post-caldera fill, most notably along the Corkscrew Canyon dike system, the interpreted northern margin of the caldera. The Dona Ana Rhyolite has yielded a whole-rock K/Ar age of 33.0 Ma (Seager et al., 1976) and $^{40}Ar/^{39}Ar$ sanidine ages of 35.49±0.11 Ma (McIntosh et al., 1991), and 36.06±0.01 Ma (Ramos and Heizler, this volume).

Dona Ana Rhyolite and collapse of the Dona Ana caldera

The impressive, south-facing escarpment of the Dona Ana Mountains, the view of the range seen from Las Cruces, is composed almost entirely of Dona Ana Rhyolite. At least 275 m thick here, the formation may be more than 450 m thick if suspected, but unconfirmed faulting has not expanded the section. Along the eastern flank of the range, a probably complete

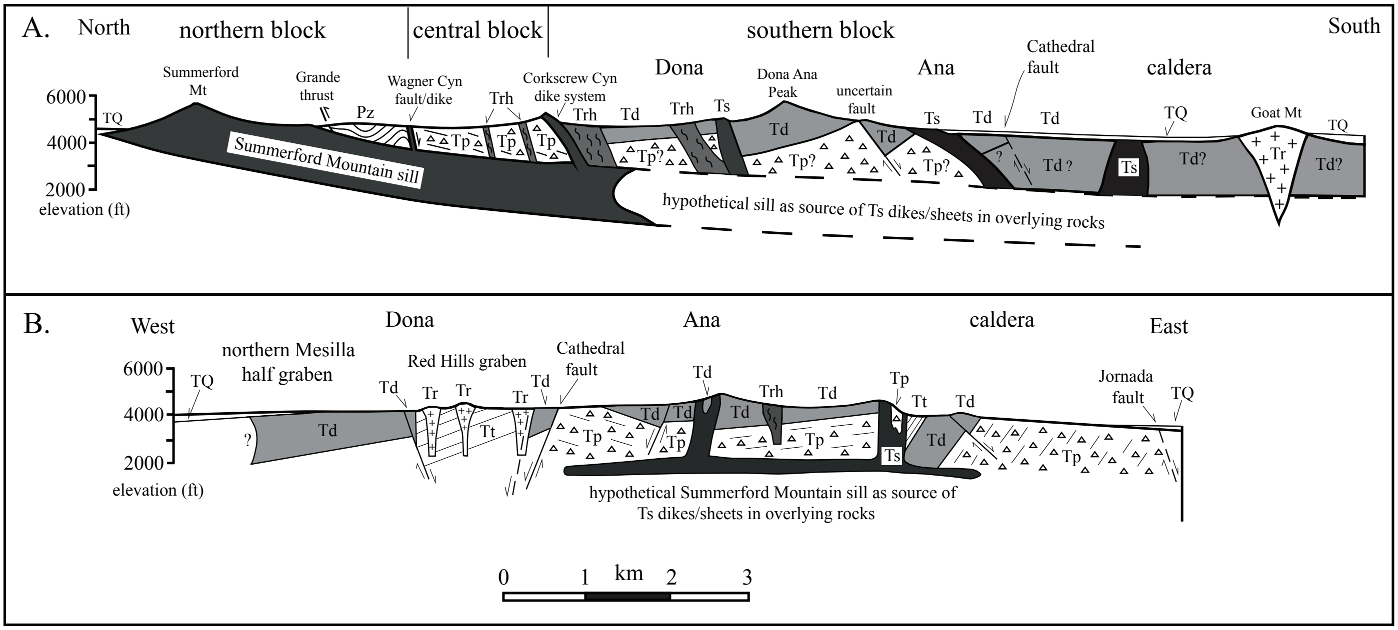

FIGURE 5. Generalized cross sections through the Dona Ana Mountains. **A**) North-South cross section from just north of Summerford Mountain to just south of Goat Mountain. **B**) West-East cross section from west of the Red Hills to just east of the buried range boundary fault. Pz=Paleozoic strata; Tp=Palm Park Formation; Td=Dona Ana Rhyolite; Tt=post-caldera tuffs, megabreccia, and rhyolite bodies; Trh=felsite and rhyolite dikes; Ts=syenite/trachyte dikes and Summerford Mountain sill; Tr=flow-banded roots of rhyolite domes associated with the Red Hills graben; TQ=latest Tertiary and Quaternary deposits.

section of the Dona Ana rhyolite is 440 m thick and was deposited unconformably on the Palm Park Formation. Elsewhere in the range, incomplete sections are at least 185 m thick.

The Dona Ana Rhyolite consists of a massive pile of ash-flow tuff. Basal parts of the tuff are discontinuous beds of fall-out tuff and tuff breccia, never more than 30 m thick. Although none of these tuffs are notably coarse grained, they may be interpreted as vent-clearing deposits. Above the basal tuffs, the main body of the Dona Ana Rhyolite is massive and without distinct breaks, except in escarpments below and adjacent to Dona Ana Peak, where crude stratification of the tuff is suggested by stacked zones of columnar jointing. Even here, however, no distinct surfaces separate the zones of jointing.

Lithology of the Dona Ana Rhyolite is distinctive, permitting it to be recognized easily in faulted outcrops throughout the southern block. Welding ranges from moderate to very dense, and eutaxitic and platy foliations are well developed throughout the formation. Locally, however, the aspect ratios of flattened pumice is so extreme that the foliation has the appearance of flow banding, especially in the thick sections below Dona Ana Peak. Outcrops of the tuff in the Cathedral Rocks area and Red Hills, which may be upper parts of the formation, are less densely welded (Fig. 1). Colors of the tuff include dark grayish purple, brown, and reddish-brown, the latter colors more typical of less-welded portions of the tuff. Locally, broad swaths of the tuff are altered to tan or pale yellow. Five to ten percent of the tuff consists of equant phenocrysts of sanidine and quartz, 2 to 4 mm in length, with sanidine generally altered to mixtures of clay and sericite. Lithic fragments locally are conspicuous, and spherulitic textures are present in some densely welded zones below Dona Ana Peak. Groundmass hematite and magnetite in the tuffs in the Red Hills give those hills their red color and impart to the tuffs notable magnetism, a property used to infer the subsurface distribution of the tuffs beneath alluvium (Seager et al., 1976). Locally, the tuff is intensely brecciated, whereas elsewhere very closely spaced sheeting gives a false impression of flow banding.

Only a few outcrops may represent eruptive vents for the Dona Ana Rhyolite. One dike, with a composition and texture similar to the Dona Ana Rhyolite or to some of the post-caldera ash-flow tuffs, transects the Palm Park Formation approximately 1.6 km southwest of Dona Ana Peak. At least 300 m long, the dike is approximately 60 m wide. Flattened pumice in this dike forms a near-vertical foliation, a feature that is difficult to understand given the normal compaction origin of pumice in eutaxitic textures. Similarly, Goat Mountain (Figs. 2, 3), composed of intrusive rocks with similar textures and mineral composition to the Dona Ana Rhyolite, is a possible vent. It is a circular intrusive with nearly vertical or inward-dipping foliation along its margins, some of which closely resembles eutaxitic foliation. Alternatively, Goat Mountain may be one of the deeply eroded, post-caldera rhyolitic or trachytic domes. Ramos and Heizler (this volume) provided a $^{40}Ar/^{39}Ar$ sanidine date for rhyolite of Goat Mountain of 35.98±0.02 Ma.

Post-caldera deposits and intrusives

Post-caldera rocks fall into two categories: fallout tuffs, ash-flow tuffs, breccias, and lava flows that accumulated above the Dona Ana Rhyolite, presumably after collapse of the caldera, and rhyolite and syenite intrusive rocks that cut across both pre- and post-caldera tuffs and breccias, as well as the northern structural margin of the caldera (Corkscrew Canyon dike system). Most of the tuffs and breccias are preserved within the intracaldera grabens or half grabens that clearly were active during post-caldera volcanic activity. The best example of this is the Red Hills graben.

The Red Hills graben (Figs. 3, 5B) is located near the inferred western margin of the caldera. Trending northwesterly, the graben is at least 3 km long and approximately 1.6 km wide. Footwalls on both sides of the structure are composed of Dona Ana Rhyolite. The graben fill, at least hundreds of meters thick, consists of a variety of mostly siliceous volcanic rocks. The bulk of the fill consists of chaotic, only locally stratified megabreccia in a matrix of altered, pale yellowish-green tuff and tuff breccia. Clasts range up to house size or larger and consist of slabs and blocks of Dona Ana Rhyolite, as well as a variety of flow-banded and non-foliated rhyolite. In addition, blocks of andesitic rocks are scattered among the debris. Some huge slabs of Dona Ana Rhyolite are clearly landslide blocks, apparently derived from the graben footwalls, whereas other blocks may be parts of block and ash flows, crumble breccia, or even blocks brought up from depth. Also present are conglomerates composed of andesitic and dacitic rock fragments, which were probably derived from the Palm Park Formation exposed along the caldera walls.

Discontinuous rhyolite bodies of variable color, texture, and shape also are present within the Red Hills graben. Individual blocks range up to hundreds of meters long and tens of meters thick. Many are apparently interbedded with the megabreccia. Their origin is always in doubt; some may be intrusive sheets, others flows, landslide blocks, or unusually large crumble breccia slabs. At least five flow-banded rhyolite masses in the form of very thick, northwesterly elongated dikes, as well as roughly funnel-shaped plutons, intrude the megabreccia as well (Fig. 3). Black vitrophyre is locally common along the margins of the intrusives. These clearly intrusive bodies are regarded as the roots of rhyolite dome/flow complexes. Some rhyolite intrusions cut boundary faults of the graben, as well as lesser faults within the graben, indicating that formation of the graben and volcanic activity within the graben were generally coeval events.

Post-caldera fallout tuff and ash-flow tuff about 300 m thick also crop out along the eastern flank of the range (Fig. 3). The deposits are within a half graben, floored by Dona Ana Rhyolite and bordered by a high-angle fault. Intruded by a thick dike of syenite (Fig. 6), the fault clearly documents an episode of block faulting of the post-caldera fill prior to emplacement of sheets and dikes of syenite within the caldera (Figs. 3 and 7). Other examples of post-caldera volcanic deposits, mostly ash-flow tuffs and fallout tuffs, are confined to small, shallow grabens and to the Southern outlier located 3 km south of Dona Ana Peak (Figs. 1, 3).

The youngest event in the caldera cycle appears to be emplacement of syenite and related dikes. Seven sheets or dikes of syenite transect the Dona Ana Rhyolite within the caldera and two cut post-caldera tuffs (one case described above; Fig. 6). Several dikes follow faults that broke caldera-fill tuffs following caldera collapse or were emplaced during or following the younger episode of post-caldera volcanism. Most important, however, is the Corkscrew Canyon dike system, which is dominated by thick syenite dikes intruded along the inferred northern margin of the caldera (Fig. 3). As much as 0.5 km in width, the northeast-trending zone narrows to the southwest, eventually becoming a belt of felsite dikes before its termination at the late Tertiary Cathedral fault (Fig. 3). Steep to moderate southern dips of the dike system can be seen where transverse canyons cross the dikes. Besides syenite, which supports steep-sided, high peaks and ridges along its length, the Corkscrew Canyon dike system also includes trachyte porphyry and rhyolite dikes adjacent to both northern and southern margins. The trachyte is interpreted to represent chilled syenite magma, but the relationship of the voluminous rhyolite to the coarse-grained syenite is unclear, mainly because contact relationships between the two very different rock types are covered by colluvium. One of the syenite dikes in the southern part of the range yielded a $^{40}Ar/^{39}Ar$ sanidine age of 32.98±0.14 Ma (Ramos and Heizler, this volume).

The syenite dikes are identical in composition and texture to the Summerford Mountain syenite sill. The sill dips southward at shallow angles, inviting the interpretation that it extends beneath both the northern and central blocks, as well as the caldera itself, thus providing a source for the trachyte and syenite dikes and sheets that invaded the Wagner Canyon fault, caldera-margin fractures, and faulted rocks within the caldera (Fig. 5A).

Structural relationships along the Corkscrew Canyon dike system are key to understanding this boundary of the Dona Ana caldera. North of the dike system, pre-caldera rocks (lavas of the Palm Park Formation) are structurally high and occupy the entire footwall of the dike system. Thick Dona Ana Rhyolite is confined to the south (hanging-wall side) of the dike system, is structurally much lower than footwall rocks, and, locally at least, is dragged up and severely brecciated adjacent to the dikes (Fig. 7). As noted above, the Corkscrew Canyon dike system narrows and disappears west of the Cathedral fault, suggesting that the caldera boundary west of this fault may have been hinged (Fig. 3). Possibly, extension in this hinged zone between the Cathedral fault and the Robledo Mountains created the Red Hills graben. The unmetamorphosed and relatively undisturbed section of Paleozoic strata exposed in the Robledo Mountains suggest that these rocks were outside the western boundary of the caldera.

The southern and eastern extent of the Dona Ana caldera is not known. Seager et al. (1976) used aeromagnetic data and

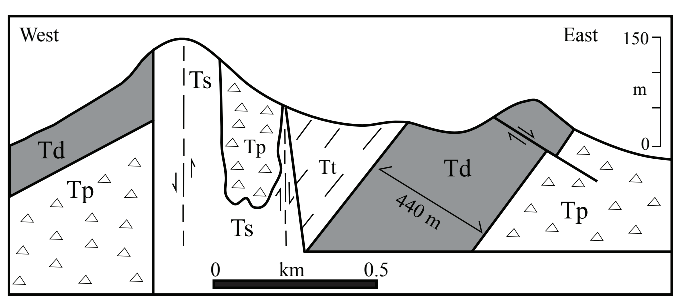

FIGURE 6. Diagrammatic west-east cross section based on a field sketch of syenite dikes (Ts) intruding faulted, post-caldera tuffs (Tt), Dona Ana Rhyolite (Td) and Palm Park Formation (Tp) along the east-central part of the Dona Ana Mountains. Unlike other figures, Ts is blank, in order to more clearly show that it intrudes the faults.

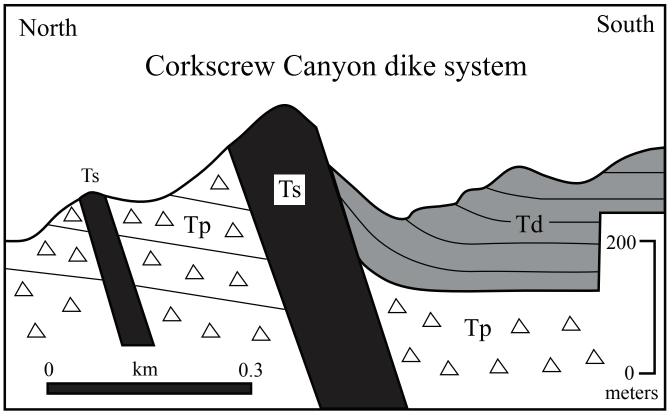

FIGURE 7. Diagrammatic north-south cross section based on a field sketch of the Corkscrew Canyon dike system. Syenite dike (Ts) separates Palm Park Formation (Tp) on the north side of the dike system from Dona Ana Rhyolite (Td) on the south side. Note drag of Td against the dike.

the magnetic nature of the Dona Ana Rhyolite, as well as the assumption that the Goat Mountain intrusion was part of the caldera complex, to infer its southern boundary (Fig. 3).

CONCLUSIONS

The bedrock in the three structural blocks of Dona Ana Mountains and the eastern boundary fault and surrounding basin-fill sediment are the result of four major tectonic and/or volcanic events in south-central New Mexico: 1) Pennsylvanian and Lower Permian sedimentary rocks exposed in the northern block were deposited during the Ancestral Rocky Mountain deformational event (Kues and Giles, 2004), either in the western side of the Orogrande Basin or on the eastern edge of the Robledo Shelf. 2) Northerly directed Laramide (latest Cretaceous-early Tertiary) compression produced folds and thrust faults in the Pennsylvanian-Lower Permian strata along the southeastern flank of the Rio Grande uplift of Seager et al. (1986, 1997). After deep erosion and onlap of the Laramide folds by the upper Love Ranch Formation, arc-related, andesitic and dacitic volcanism and volcaniclastic sedimentation of the Palm Park Formation completed the onlap of Laramide topography in late Eocene time. Arc volcanism and Laramide compression were probably both a response to northeastern subduction of the Farallon plate and are considered part of the same tectono-volcanic event (Amato et al., 2017). 3) Silicic volcanism formed the latest Eocene Dona Ana caldera, whose rocks, which are primarily exposed in the southern structural block, include ~440 m of ash-flow tuffs of the Dona Ana Rhyolite erupted during caldera collapse, and post-caldera fallout tuffs, ash-flow tuffs, breccias, and flow-banded rhyolite flow/dome complexes. Syn- and post-caldera rocks were crosscut by syenite and felsite dikes, which may have been fed by the Summerford Mountain sill. 4) During crustal extension of the southern Rio Grande rift, the Dona Ana Mountains were uplifted along the Jornada fault on the east side of the range and gently tilted westward. Initial movement on the Jornada fault probably occurred in middle Miocene time, while subsequently the Dona Ana block became the hanging wall of the northern Mesilla Valley half graben, whose footwall is the Robledo Mountains. The Jornada fault east of the range shows no evidence of Quaternary activity, but the Jornada fault on the north side of the range has evidence of ~50 m of post-0.8 Ma movement. Early Pliocene to Quaternary piedmont-slope and axial-fluvial sediment have onlapped much of the range.

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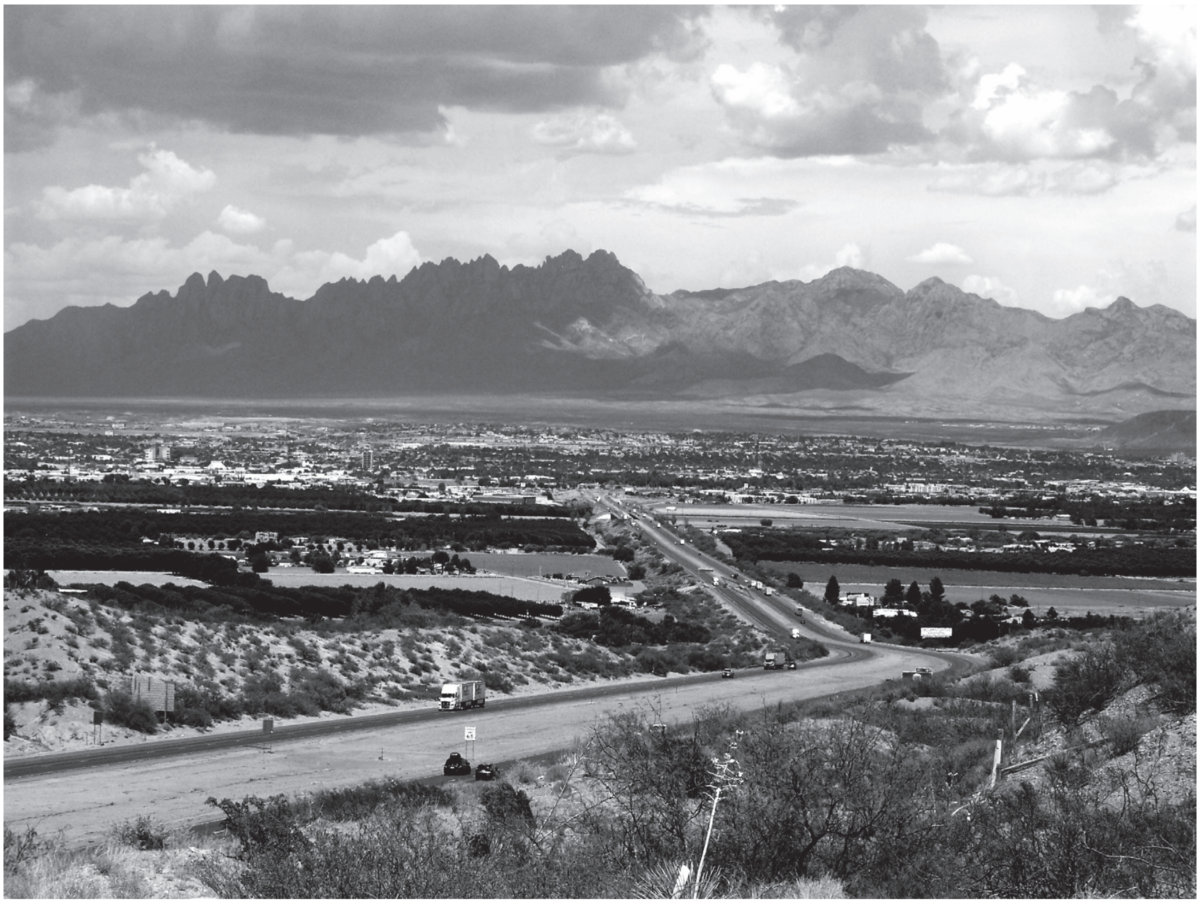

View to the east of the Mesilla Valley and Las Cruces from the West Mesa. The Organ Mountains are in the background. Photograph by Greg H. Mack.