Geology and Geomorphology of the San Bernardino Valley, Southeastern Arizona

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ABSTRACT

Geologic and geomorphologic data form the basic foundation for combined ecosystem and land-use management in the AZ-NM Borderlands Region. We have described and integrated the surficial geology, bedrock geology, and soil types of the valley at a scale of 1:24,000 for use by the ranching, land management, and research communities. Future investigations will study the relationships between vegetation distributions and the combined soil-bedrock units.

The San Bernardino Valley is dominated by a Pleistocene basaltic volcanic field with more than 130 separate vents, associated lava flows, and pyroclastic deposits. Monogenetic pyroclastic cones are the most prominent features in the valley, which suggests relatively benign Strombolian-style eruptions were the typical volcanic activity in the field. Several of the larger landforms have multiple eruptive vents. Lava flows, ranging in age from 260 ka to 750 ka, are typically thin, cover a fairly limited area, and form a series of overlapping surfaces. The approximate extent of individual flows can be mapped, although most flow surfaces are now grasslands mantled with clay-rich vertisols and basalt cobbles, with few primary flow features preserved. Steam-blast eruptions occurred in at least eight places, resulting in distinctive maar craters and tuff rings. Older flows (ranging 1-8 my) emanated from the Peloncillo and Pedregosa Mountains and flowed into the valley. Basalt flows and pyroclastic deposits of both periods form an important part of the modern basin fill. Multiple flows, separated by alluvial gravels, have been penetrated by wells drilled in the valley.

Sediments eroded from the adjacent mountains and deposited into the valley as alluvial fans are also an important component of the basin fill. These deposits consist of moderately to poorly sorted conglomerates and form the groundwater aquifers in the valley. Soils developed on alluvial deposits of different ages have distinctive characteristics. Deposits representing the Plio-Pleistocene, Pleistocene, Holocene, and modern have been differentiated based on geomorphic characteristics, pedogenic features, and stratigraphic relationships. Relief on these alluvial surfaces is very minimal north of Paramore Crater, whereas erosional incision is more pronounced to the south and exposes the interbedded nature of the basaltic units and alluvial units. Recent integration of this valley into the Rio Yaqui system has caused downcutting by the streams in the southern portion of the map area.

INTRODUCTION

The purpose of this project is to integrate new detailed field mapping, aerial photograph interpretation, previous research, and other available data into 1:24,000 scale geologic and geomorphic maps of the San Bernardino Valley study area (Map Pocket). Our goal is to describe the fundamental surficial and bedrock geology in a manner that can be incorporated into ecosystem and land-management research. Future work will integrate our geologic maps with soil and vegetation surveys for this portion of the Borderlands Region.

The study area is in the extreme southeastern corner of Arizona in Cochise County (Figure 1). It is bounded on the south by the U.S.- Mexico border, on the east by the Arizona-New Mexico border, on the west by the Perilla and Pedregosa Mountains, and on the north-northwest by U.S. Highway 80. The main geographic features in the study area include the northern half of the San Bernardino Valley, the southern portion of the San Simon Valley, and the western side of the Peloncillo Mountains. The valleys formed during the Miocene-Pliocene period of high-angle normal faulting (the Basin and Range Disturbance) that produced alluvial basins of variable depth separated by bedrock mountains. The basins subsequently filled with volcanic and sedimentary deposits shed from the adjacent mountains and volcanic rocks erupted in the valleys.

The San Simon Valley is an alluvial valley that lies between the Peloncillo Mountains on the east and the Chiricahua Mountains on the west. A north-northwest trending drainage divide extends from the vicinity of

Paramore Crater toward the Chiricahua Mountains and separates San Simon Valley from San Bernardino Valley to the southwest. Topographic relief associated with this drainage divide is minimal and the geologic nature of the divide is uncertain. Streamflow in San Simon Valley is to the north and northwest into the Gila River system. Gravity data suggests that San Simon Valley may be approximately twice as deep as San Bernardino Valley (Lysonski et al., 1981; Oppenheimer and Sumner, 1980).

The Peloncillo Mountains are composed of 24 to 30 million-year-old rhyolitic, dacitic, and andesitic rocks that overlie a basement of Paleozoic and Mesozoic sedimentary rocks (Wrucke and Bromfield, 1961). Portions of three separate calderas have been previously mapped within the study area. One of these volcanoes, informally named the Rodeo caldera after the nearby village, erupted several ash-flow and lava sequences that comprise the Peloncillos on the east side of the southern San Simon Valley (Deal et al., 1978). Indeed, the center of the caldera may be buried beneath the San Simon Valley. The youngest of the rhyolite eruptive centers, the Clanton Draw caldera (McIntyre, 1988), probably produced the thick tuff beds in Skeleton Canyon. A steep eastward-dipping contact between the Tuff of Skeleton Canyon (map unit Tscn) and older rocks is exposed in Skeleton Canyon and may be the structural margin of the caldera. A third caldera, the resurgent Geronimo Trail caldera (Deal et al., 1978; Erb, 1979) has been postulated in the southern end of the mountains just north of the international border, although most of this feature is in New Mexico. A northwest-striking normal fault (the Baker Canyon fault) down-drops homogeneous and heterogeneous volcanic breccia on the east against Paleozoic and Mesozoic carbonate rocks on the west. The fault extends southeastward across Baker Canyon where it appears to form a high-angle topographic margin separating breccias of different compositions. Our mapping indicates the ring-fracture domes originally mapped by Erb (1979) are andesite breccias. South of the divide separating Baker Canyon from Guadalupe Canyon, volcanic breccias overlie a slightly west-dipping erosional unconformity, which may be a topographic margin of a smaller caldera within the Geronimo Trail caldera. Approximately 400 m of ash-flow tuff beds fill the inside of the possible Geronimo Trail caldera.

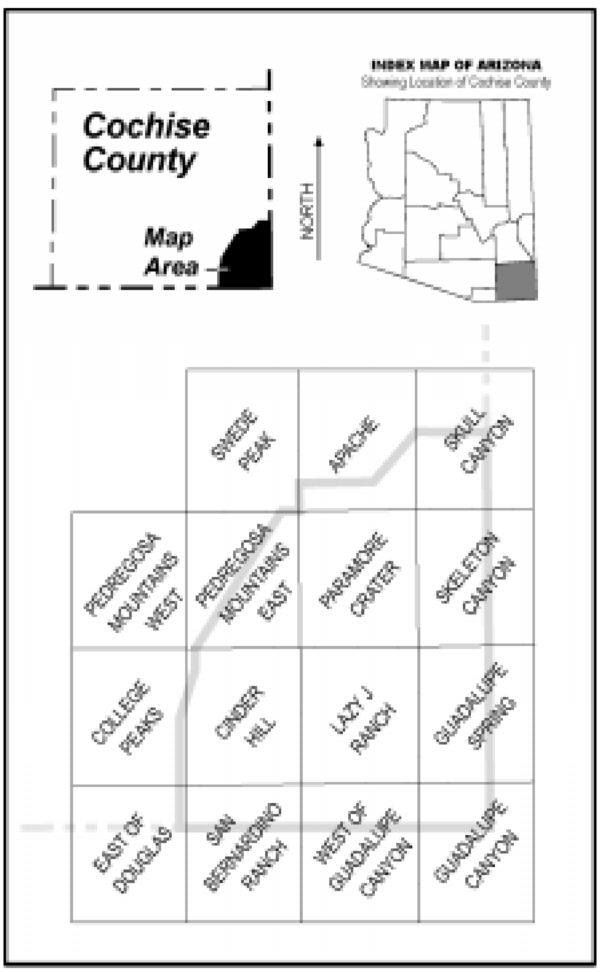

Figure 1. Index map of southeastern Arizona showing 7.5' quadrangles included in the San Bernardino Valley project area (outlined in gray).

Three mountain ranges form the western and northern margins of San Bernardino Valley. The Perilla Mountains form the western margin of the valley and are composed of Mesozoic sedimentary rocks, Tertiary andesite and welded tuff, and Late Tertiary – Quaternary basalts (Cooper, 1959; Drewes, 1980). The Pedregosa Mountains to the west-northwest of the valley are formed from Late Paleozoic and Mesozoic sedimentary rocks, Mesozoic and Tertiary volcanic rocks, and Late Tertiary – Quaternary basalts (Drewes and Brooks, 1988). Except for the young basalts, the bedrock in the Pedregosas has been faulted and deformed by multiple tectonic events. The Late Tertiary – Quaternary basalts erupted from both mountain ranges probably flowed into the adjacent San Bernardino Valley and were down-dropped by high-angle normal faults. The Chiricahua Mountains to the north are composed mostly of Tertiary rhyolite, although there are Paleozoic and Mesozoic sedimentary rocks exposed on the southern end (Drewes, 1980; Marjaniemi, 1969; Pallister, 1989).

San Bernardino Valley, the primary focus of our work, is an elongated, southwest-trending, gently sloping basin situated between approximately parallel mountain ranges. Gravity data suggest the alluvial basin is less than 1600 feet deep (Oppenheimer and Sumner, 1980). Approximately one-half of the basin is in Arizona and the other half is in Sonora, Mexico, but only the U.S. portion of the valley is included in this study. The basin is about 30 km wide at the international border and narrows to about 20 km wide at its northeastern end. The highest elevation in the valley is 5135 ft. on a cone north of Paramore Crater, and the lowest elevation is 3700 ft.

in Black Draw where it crosses the international border. The average topographic gradient along the valley floor is 49 feet per mile (Schwab, 1992). Black Draw and its tributaries drain the San Bernardino Valley and flow southward into Mexico, where the trunk stream is known as Rio San Bernardino, part of the Rio Yaqui system.

The geology of the San Bernardino Valley is comprised of three distinct elements. Paleozoic and Mesozoic sedimentary rocks and mid-Tertiary volcanics probably form the bedrock floor of the basin. Tertiary and Quaternary alluvial deposits (and basalt flows from vents in the adjacent mountains to the east and west that predate formation of the basin) filled the basin, although erosion is removing some of the earlier deposits. Tectonic activity along range-bounding normal faults may also have contributed to the cycles of down-cutting and deposition by changing the base levels of drainages in the region. During the Pleistocene, the basaltic volcanic field that dominates the present landscape was active and produced numerous thin basalt lava flows and pyroclastic deposits that are commonly interbedded with the alluvial sediments. Basalt flows and pyroclastic deposits form an important portion of the basin fill in the valley.

CLIMATE

The study area is in the northern portion of the Chihuahuan Desert and the present climate of the San Bernardino Valley is that of a semiarid grassland. The nearest weather station to the valley is in Douglas, Arizona (elevation 4000 feet asl), where the average recorded daily maximum temperature from 1964 to 1994 was 79.1^{o}F and the average daily minimum was 44.7^{o}F (Western Regional Climate Center). Average temperatures in the San Bernardino Valley may be slightly lower as a result of the higher elevation of the valley. Average annual precipitation at Douglas is 14.6”, with approximately 67 percent falling during the July through October monsoon thunderstorm season.

The climate of the Chihuahuan desert has not remained constant over the time period represented by the alluvial deposits and surfaces in the study area. The transition from the relatively warm and stable Pliocene climate to the dramatic glacial-interglacial cycles of the Pleistocene resulted in major aggradation and erosion events recorded as alluvial fans and fan remnants in the study area. Annual precipitation was probably substantially greater during the late Pleistocene than the present (Spaulding and Graumlich, 1986), which, combined with reduced seasonal extremes, apparently caused the late Pleistocene climate to be more conducive to weathering of bedrock and soil minerals than the dry interglacial moisture regime of the present. Late Pleistocene to early Holocene (approximately 12 to 9 ka) was a period of two distinct pluvial episodes, the first characterized by lowered temperatures and enhanced winter rainfall, the second by temperatures similar to the modern with enhanced monsoons (Spaulding and Graumlich, 1986). The present climatic and vegetational regimes were established after about 8000 years B.P. as winter precipitation was reduced and the summer monsoon expanded in much of the southwest; middle Holocene wet climates probably favored development of grassland and the widespread loss of well-developed, mature soils (Van Devender and Spaulding, 1979).

PREVIOUS WORK

Prior to this project, the geology of the San Bernardino Valley had never been mapped in detail. One of the earliest descriptions of the area (Darton, 1933) reported extensive lava tubes and included a diagram of Paramore maar. However, we found only one lava tube during our study (Figure 2). Later geologists have worked in and around the San Bernardino Valley, although most have focused on the adjacent mountains and mapped the valley only on a reconnaissance basis (Cooper, 1959; Drewes, 1980; Drewes, 1981; Drewes and Brooks, 1988; Lynch, 1972). Detailed bedrock mapping of two areas with exposures of the Paleozoic and Mesozoic bedrock on the east side of the valley just north of the international border was done by two M.S. students at the University of Arizona (Dirks, 1966; Kelly, 1966). Others contributed detailed analyses and interpretations derived from geochemical and petrological studies of the basaltic rocks and the interesting suite of mantle-derived xenoliths found in the valley lavas (Arculus et al., 1977; Evans and Nash, 1979; Kempton et al., 1987; Kempton et al., 1982; Kempton et al., 1991; Lynch, 1978). Samples from valley and flank basaltic lavas and adjacent rhyolite centers in the mountains have been described and dated to help ascertain the geologic history of the valley

Figure 2. Lava tube in basalt flow west of Cinder Hill, Cinder Hill quadrangle. Lava flows in valley basalts are typically thin (5-20 m).

(Damon et al., 1996; Deal et al., 1978; Kempton et al., 1987; Lynch, 1978; Marvin et al., 1978; Reynolds et al., 1986). Hydrologists have studied the drainage system of the valley and the quality of groundwater (Anderson, 1995; Anderson et al., 1992; Robertson, 1991; Schwab, 1992). Additional hydrological studies are currently being conducted by researchers at New Mexico Tech in Socorro (Earman et al., 1999). Detailed soils maps have been prepared by the U.S. Department of Agriculture, Natural Resources Conservation Service (McGuire, 1998).

GENERAL GEOLOGY AND GEOMORPHOLOGY

The Late Cenozoic period of basaltic volcanism resulted in the eruption of more than 130 separate vents and associated lava flows and pyroclastic deposits. Limited radiometric dating indicates the exposed rocks of the San Bernardino volcanic field were erupted between 750,000 and 260,000 years ago (Kempton et al., 1987; Lynch, 1978; Reynolds et al., 1986). Monogenetic pyroclastic cones are the most prominent features in the valley, which suggests that relatively benign Strombolian eruptions were the typical volcanic activity. Cinder cones, with varying amounts of bombs, vent lava, and agglutinate breccia, are the most common landforms in the valley. Several of the volcanic features have multiple eruptive vents and some cones have been partially obliterated by subsequent eruptions. The cones show a wide range of erosional morphology from well-formed, moderately eroded cones to rounded, subdued hills. Some vents are so degraded that they are best recognized from aerial photography. Steam-blast (or "phreatic") eruptions, which occurred when ascending alkali basalt magma came into contact with groundwater-saturated basin-fill sediments, are found in at least eight places in the valley. These features can be distinguished from other vents by their distinctive craters rimmed with light-colored tuff rings (Figure 3) and surge deposits (unit Qps). These pyroclastic deposits formed from violent explosions that occurred before much magma reached the surface, as the tuff rings and surge beds are often dominated by accidental sedimentary and felsic volcanic rock debris from the basin-fill sediments (Figure 4). The best example of these 'phreatomagmatic' features is Paramore Crater (Figure 5), a maar crater approximately 1.5 km in diameter.

Basaltic lava flows are exposed across the San Bernardino Valley, although the source vents for the individual flows are not always apparent. Geochemical studies indicate the flows are alkaline in composition (basanite to mugearite) and high in magnesium (Kempton, 1984; Kempton et al., 1984a; Lynch, 1978). Most of these low-viscosity flows spread out as thin sheets over significant areas and flow toward the south, following the modern slope of the valley. Some flows also bevel and cover older lavas or pyroclastic deposits (cinder cones). Primary flow features (e.g., pahoehoe festoon structures) are preserved on some of the youngest flows (especially on aerial views). Pressure ridges and levees, a few meters higher than the surrounding flow surface, and scattered hornitos (small splatter cones on lava flows) are present (Figure 6). Soils formed on the lava flows are chocolate brown, rocky, clay-rich (smectitic) vertisols that develop deep cracks when dry (Figure 7).

Older lavas, previously described as "flank lavas" (Kempton, 1984), are exposed along the Pedregosa and Perilla (to the west) and Peloncillo (to the east) mountain fronts flanking the San Bernardino Valley. Normal faulting has down-dropped these flows along the margins of the valley and some of them probably continue some distance out into the valley interbedded with basin-fill deposits (Figure 8). Limited age dating suggests the flank lavas on

Figure 3. False-color aerial photograph of the Paramore Crater (V1135a) area. Note the light-colored surge deposits that comprise the tuff ring around much of the crater (younger eruptions obscure the tuff ring on the east-southeast margin). A smaller, partial tuff ring (V2112) is present approximately 1.5 km to the southeast of Paramore. Several outcrops of Paleozoic limestones surrounded by basalt lavas are present south of Paramore Crater.

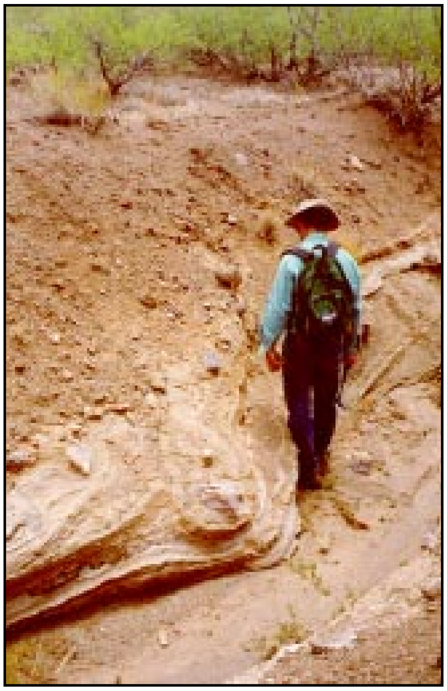

Figure 4. Outcrop of surge beds on the west side of the Paramore Crater tuff ring (V1135a). Many of the larger clasts are light-colored rhyolite and sedimentary rock fragments from the underlying basin-fill sediments.

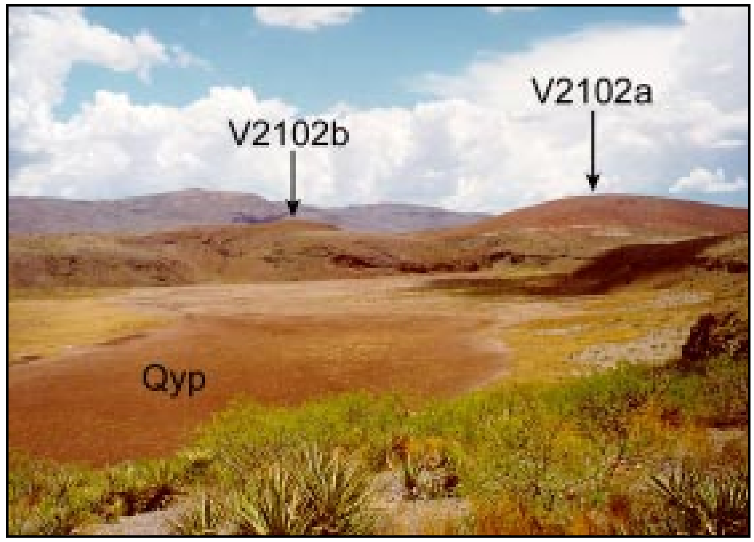

Figure 5. View southeast into Paramore maar (V1135a). A pre-maar basalt flow, capped with tuff ring deposits, forms the southern (right) margin of the crater. Subsequent volcanoes (V2102a, right, and V2102b, center) covered or destroyed part of the tuff ring. The floor of the maar is covered with playa lake sediments (Qyp).

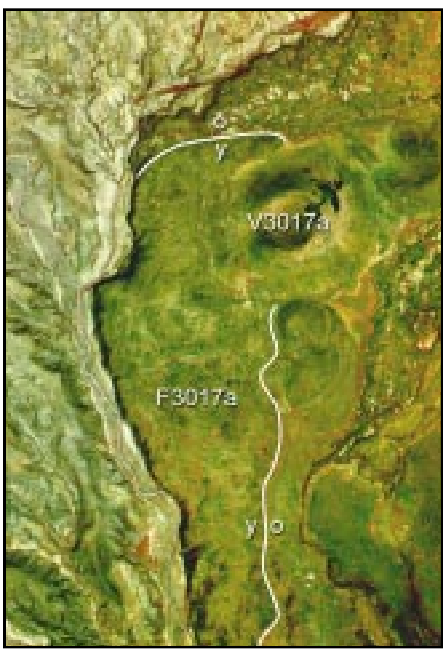

Figure 6. False-color aerial photograph of the Cinder Hill area. Recent cinder mining is evident on the northeast flank of Cinder Hill volcano (V3017a). This is one of the youngest eruptions in the San Bernardino field and primary flow features are still evident on the surface of the lava flow (F3017a).

Figure 7. Typical lava flow surface (F4003) in the San Bernardino volcanic field (San Bernardino Ranch quadrangle). Angular to subangular boulders and cobbles of vesicular basalt are abundant; soils are chocolate brown to reddish brown and very clay-rich vertisols.

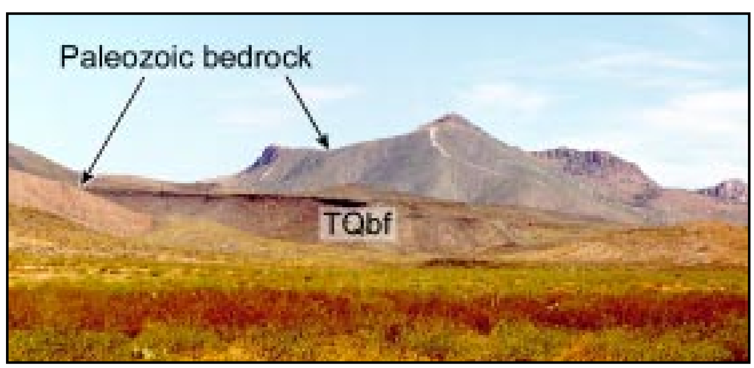

Figure 8. Basalt flank lava flow (TQbf) from the Pedregosa Mountains on the western margin of San Bernardino Valley, Pedregosa Mountains East quadrangle.

the west are Pliocene (4.72 ±0.07 Ma in Hog Canyon, 3.23 – 3.01 ±0.04 Ma in Mulberry Canyon) to early Pleistocene (1.48 ±0.02 Ma northwest of Krentz Ranch). Four dated localities in the Peloncillo Mountains (9.20 ±0.1 Ma, 5.63 ±0.08 Ma, 4.95 ±0.07 Ma, and 3.62 ±0.14 Ma) have late Miocene to Pliocene ages (Kempton, 1984). Kempton (1984) noted slight petrographic differences between flank lavas and valley lavas, but reported all the flank lavas were alkaline in composition (basanite to mugearite), similar to the younger flows. We found that fresh samples of the older lavas are typically indistinguishable from the younger lavas. The flank lavas are typically much thicker than valley flows, with some sequences up to 300 feet thick. The surfaces of flows have been eroded and deeply dissected by drainages. As a result of more extensive weathering, flow features, vent structures and significant pyroclastic deposits were more difficult to recognize in these older basalts, especially on the east flank. Thus, it was not possible to determine the original sources for most of the individual flows. The older basalts fill paleo-valleys and outcrop at the top of ridges, suggesting the flows erupted over paleotopography that was similar to the modern terrain.

Surficial geologic units in the project area are differentiated by sediment source, process of emplacement of the deposits, and relative age. The physical characteristics of sedimentary units and surfaces (ie., alluvial fans, river channels, or stream terraces) are shaped by large-scale fluvial processes. However, if the initial surfaces formed by such deposits are not buried by subsequent deposits or destroyed by erosion, they are gradually modified over thousands of years by other processes. Such modifying processes may include (1) the development of soils, primarily through the accumulation of silt, clay, and calcium carbonate and the chemical breakdown of original rock constituents; (2) small-scale erosional and depositional processes, including bioturbation, that smooth the original surface topography; (3) the development of surficial gravel pavements ("desert pavements") above zones of accumulated clay and silt; (4) the development of dendritic tributary stream networks on alluvial surfaces; (5) entrenchment of secondary streams below the original depositional surfaces and subsequent dissection of those surfaces. These geomorphic processes operate very slowly in semiarid environments like the San Bernardino Valley.

Alluvial surfaces of similar age have a characteristic appearance because they have undergone similar post-depositional modification. As there are distinct differences between younger and older surfaces, the ages of alluvial surfaces in the southwestern United States may be roughly estimated based on surface characteristics, especially the extent of soil development (Bull, 1991). Old surfaces that have been isolated from deposition or reworking for hundreds of thousands of years are characterized by strongly developed soils with thick clay- and calcium carbonate-rich horizons; such surfaces may also have smooth, closely packed desert pavements of strongly varnished surface rocks above entrenched drainages. Young fan surfaces often retain characteristics of the original depositional topography, show minimal development of soil, desert pavement, or rock varnish, and are basically undissected.

Sediments eroded from the adjacent mountains and deposited in the main valley as alluvial fans and stream terraces are an important component of the modern basin fill. These deposits consist of moderately to poorly sorted conglomerate, finer fluvial facies, paleosol horizons, and unsorted debris flow deposits. Many different lithologies are represented in the coarse fraction. Relief on these alluvial surfaces is very minimal in the northern portion of the San Bernardino Valley and middle Pleistocene (Qm) surfaces typically are the oldest alluvial surfaces exposed (Figure 9). Accumulation of eolian sediments also appears more pronounced on aerial photographs of the northern end of the valley. Erosional incision is more pronounced along the international border and on the western side of the basin in the Silver Creek drainage. Remnants of late Tertiary to early Quaternary alluvial fan surfaces are exposed in these areas and the interbedded relationship of younger alluvial units and basalt flows is evident (Figure 10). In other areas of San Bernardino Valley, alluvial deposits of middle and late Pleistocene ages form a thin veneer over basalt flows. These alluvial deposits are undoubtedly important for groundwater recharge and probably form a complex system of aquifers interbedded with impermeable basalt flows in the San Bernardino Valley, although not much is known about the subsurface relationships.

The presence of Paleozoic outcrops located out in the basin (Cooper, 1959), surrounded by Quaternary basalt and alluvial material, suggests that much of the eastern half of the

Figure 9. Middle Pleistocene (Qm) alluvial surface in the northern portion of the study area, Pedregosa Mountains East quadrangle. Clasts are subangular to subrounded and are comprised of a mixture of basalt, rhyolite, and sedimentary rocks. Soils are typically orange to orange-brown. Red Hill (V1025a) in background.

Figure 10. Interbedded alluvial deposits and basalt flow in Cottonwood Draw, Lazy J Ranch quadrangle. Basalt flow forms the prominent black ledge and it is covered by Qm gravels (light orange matrix containing clasts of mixed lithologies that are partially carbonate-coated); late Tertiary to early Quaternary (TQo) alluvial fan deposits underlie the basalt (partially obscured by basalt- and Qm-derived colluvium).

modern valley is a buried pediment where bedrock is quite shallow (see Sheet 2 and Figure 3). Therefore, the main basin-forming graben probably occupies only the western half of the modern valley. The traces of the main faults and any subsidiary faults are difficult to recognize in the bouldery alluvium. Lynch (1972) suggested the basaltic vents followed fault zones, a conclusion that is uncertain with available data.

The most recent significant earthquake in the region was the great Sonoran earthquake of 1887 that produced a 75 km-long scarp on the Pitaycachi fault along the east side of the San Bernardino Valley south of the international border (Bull and Pearthree, 1988; Sumner, 1977). Seismic hazard studies in the valley north of the border have recognized 3 to 6 Quaternary events along the eastern side of the valley (approximately along the trend of the 1887 event) (Machette et al., 1986; Pearthree, 1986), all of which are east of the Paleozoic outcrops. Two possible Quaternary events have been identified on the western side of the valley (Machette et al., 1986; Pearthree, 1986).

MAPPING TECHNIQUES AND GROUND CONTROL

We employed standard bedrock and surficial geologic mapping techniques to produce 1:24,000-scale geologic maps of the project area (Map Pocket). The project area included the Cinder Hill, Paramore Crater, and Lazy J Ranch 7.5' quadrangles, plus portions of nine adjacent quadrangles (Apache, Pedregosa Mountains East, College Peaks, Skull Canyon, Skeleton Canyon, Guadalupe Spring, Guadalupe Canyon, West of Guadalupe Canyon, and San Bernardino Ranch). A combination of detailed field surveys of natural exposures, reconnaissance mapping, and examination of previous published and unpublished mapping was used to describe the area. Reconnaissance mapping was based primarily on interpretation of 1:33,600-scale black and white aerial photographs (taken in February 1988) borrowed from the Cochise County Highway Department in Bisbee. These were supplemented by color aerial photographs (approximately 1:24,000-scale) that were taken for the U.S. Forest Service in May 1995 and false-color infrared aerial photographs (approximately 1: 47,260 scale) in portions of the project area.

Individual cones are designated by a four digit number (ie., Vxxxx) based on location on the township and range grid system, with a subscript 'a', 'b' and 'c' if multiple vents are in the same section. For example, a vent located in T21S, R31E, Section 22 is labeled "V1122". With the exception of features named on published topographic maps, such as Paramore Crater (V1135a) and Red Hill (V1025a), we did not use local names or previously published or unpublished informal names for volcanic cones or other features. From aerial photographs and field mapping, original extent of individual lava flows can be determined for many of the flows, although most are now rocky, deeply weathered flat grasslands with few remnant flow features. When possible, the lava flows are labeled with the number of the source vent (e.g., a flow from V1122 is labeled "F1122"). Where basaltic units are in contact, stratigraphic position is indicated by "Y" (younger) and "O" (older) when the relationship can be determined.

DESCRIPTION OF MAP UNITS SURFICIAL DEPOSITS

Surficial deposits on the accompanying maps are classified by inferred age. Ages of these deposits are roughly estimated by correlation with other similar areas and geomorphic character (soil development, color, soil carbonate accumulation, relative stratigraphic position, relief, rounding on interfluves, depth of channels, etc.), because no useful constraints have been developed for most of the surficial deposits in the study area. Likewise, correlations between units of the same age in different locales of the project area are not straightforward due to the variable source areas. Each map unit represents a range of each characteristic so that the ages of the alluvial surfaces range from next youngest to the next oldest unit. Time did not permit examination of each surface and some discrepancies may exist between surface features and specific units.

Deposits are divided by age into the Miocene-Pliocene (Tsa, Tsy), the Plio-Pleistocene (TQo), early to middle Pleistocene (Qmo), middle Pleistocene (Qm_1, Qm_2, Qm, and Qmi), middle to late Pleistocene (Qml), late Pleistocene (Ql and Qli), late Pleistocene to Holocene (Qly), and Holocene to modern (Qy, Qyp, and Qc). Basalt-dominated colluvium (Qcb) and alluvium (Qab) are mapped on the flanks and

Figure 11. Incised Holocene alluvium (Qy) above the active channel of Cottonwood Draw, Lazy J Ranch quadrangle. Note the stratified, fine-grained nature of the deposits and the significant amount of organic material present in several horizons.

immediately adjacent to the cones. Map units are based on surface expression, which may be younger than that of the surface deposit. Thus, a map unit may be relatively young but contain characteristics of older deposits.

Qy Holocene alluvium (<10 ka). Alluvial deposits in active stream channels composed of unconsolidated sand to small boulders that reach several tens of centimeters in diameter upstream but are smaller and fewer downstream. These deposits are locally dissected as much as 2 meters by narrow entrenched main channels and tributary channels (not mapped separately). **Qy** deposits are characterized by stratified, poorly to moderately sorted sands, pebbles, and cobbles commonly mantled by sandy loam sediment (Figure 11). The main channel (where not appreciably dissected) may diverge into braided channels. Surfaces locally exhibit bar and swale topography, with the bars being typically more vegetated. Soil development is weak with only slight textural and structural modifications of B horizons and slight calcification (Stage I). Some of the older **Qy** soils may contain weakly developed argillic horizons. Because surface soils are not indurated with clay or calcium carbonate, **Qy** surfaces have relatively high permeability and porosity.

Qyp Playa lake deposits that have accumulated in the bottoms of maar craters and other closed depressions. The sediments consist of fine sand, silt, and clay deposited by ephemeral streams, slope run-off, and the wind. Pebbles and cobbles of basalt are scattered across the playa surface.

Qab Alluvial deposits in active drainages emanating from or immediately adjacent to volcanic cones and on the surfaces of basalt lava flows (Figure 12). The deposits are characterized by partly stratified, poorly to moderately sorted sands, pebbles, and cobbles mantled by sandy loam sediment derived from basaltic parent material. **Qab** often grades

Figure 12. Basalt-dominated alluvial cover (Qab) in an active drainage approximately 1.5 km west of Paramore Crater. Alluvium is composed of poorly sorted angular to subangular basalt debris 1 to 1.5 m thick, except where recently scoured out of the active channel, overlying yellowish brown basaltic tuff (Qbpt) and black flow (Qbf) beds.

downstream into **Qy** deposits and upstream with **Qcb** deposits.

Qc Hillslope colluvium Unconsolidated to weakly consolidated, poorly sorted pebble- to boulder-sized rubble that forms an apron at the base of hillslopes as a result of physical and chemical weathering of up-slope bedrock. The composition of the angular to subrounded clasts reflects the lithologies of the source area and gravity is the main transport mechanism.

Qcb Unconsolidated to weakly consolidated, poorly sorted pebble- to boulder-sized basaltic material that forms a rubble apron at the base of volcanic cones and at some margins of lava flows. May be gullied by runoff, which is a main characteristic used in aerial photograph interpretation of the deposits. **Qcb** is typically transitional to **Qbpc** or **Qbpb** on the flanks of cinder cones and transitional with **Qab** at the slope break at the base of the cones.

Qcl Unconsolidated to weakly consolidated, poorly sorted pebble- to boulder-sized colluvium dominated by limestone and/or dolomite detritus eroded from adjacent slopes. Soils are typically weakly-developed with high carbonate content and cream to light brown in color.

Qly Holocene and Late Pleistocene alluvium, undivided. Alluvial deposits along active channels that are intermediate between **Qy** and **Ql** surfaces. The surfaces are typically narrow and elongated parallel to the drainage and are of limited extent, although **Qly** surfaces in the southern San Simon Valley are more areally extensive. The surfaces have weak soil development and limited incisement. Subtle differences in relative elevation are the main features used to distinguish **Qly** from lower **Qy** deposits and higher **Ql** surfaces.

Ql Late Pleistocene alluvium (10 to 150 ka). Alluvial fan deposits composed of moderately to poorly sorted, clast-supported conglomerates, sandstones, siltstones, and paleosols (Figure 13). Clasts are subangular to subrounded pebbles and small cobbles of felsic and mafic volcanic and, locally, sedimentary rocks. The surfaces are typically light gray to light brown in color. **Ql** surfaces are moderately incised by stream channels but retain constructional, relatively flat interfluvial surfaces. **Ql** soils typically have weak to moderately clay-rich argillic horizons, although some contain much pedogenic clay and some calcium carbonate, resulting in relatively low infiltration rates. Clasts may have thin discontinuous coatings of carbonate.

Figure 13. Cutbank exposure of late Pleistocene (Ql) alluvial fan deposits on the west side of Silver Creek, Cinder Hill quadrangle. Deposits are typically weakly indurated poorly sorted conglomerates with a mixture of clast lithologies.

Qli Alluvial fan deposits similar to **Ql** that were deposited as a thin veneer of material on older basalt lava flows. Soils tend to be somewhat more brown than typical **Ql**. In the field, these surfaces are difficult to distinguish from weathered lava flow surfaces, as only scattered non-basaltic clasts indicate alluvial origin, but they can be recognized from aerial photographs.

Qml Middle and late Pleistocene alluvium, undivided. Discontinuous alluvial surfaces, usually confined to stream terraces and remnants along the major washes, that exhibit subtle intermediate topographic position between definite **Ql** deposits and higher older **Qm** fan surfaces.

Qm Middle Pleistocene alluvium (150 to 750 ka). Alluvial fan deposits composed of moderately to poorly sorted conglomerate containing subangular to subrounded clasts of felsic volcanic rocks and limestone. Lenses of channel-fill fluvial sands, unsorted and unbedded debris flows, and argillic paleosols are also locally present. Typically the **Qm** deposits are coarser than the younger **Ql** sediments and the clasts commonly have thin coatings of carbonate. These deposits may locally contain thick argillic horizons and Stage III carbonate development, resulting in rapid sheet-flow runoff and low infiltration rates. In areas of the study area adjacent to limestone bedrock, these deposits contain limestone clasts surrounded by a moderately to strongly cemented matrix of carbonate (Stage III-IV). Variable clast lithologies make it difficult to correlate the unit between different areas of the study. Typically the **Qm** deposits are orange to orange-brown in the northern portion of the study area (see Figure 9), but are medium brown to gray in the southern portion. Surface clasts commonly exhibit a weak to moderate orange-brown varnish. The deposits form relatively broad flat surfaces north of Paramore Crater and in the San Simon Valley, but they are deeply incised in the Silver Creek and Hay Hollow Wash drainage basins. In these incised areas in the southern and western portions of the study area, multiple **Qm** surfaces can be recognized based on relative topographic position (Figure 14).

Qm$_1$ The oldest and topographically the highest of the **Qm** alluvial deposits, **Qm$_1$** forms a 2- to 5- meter cover over

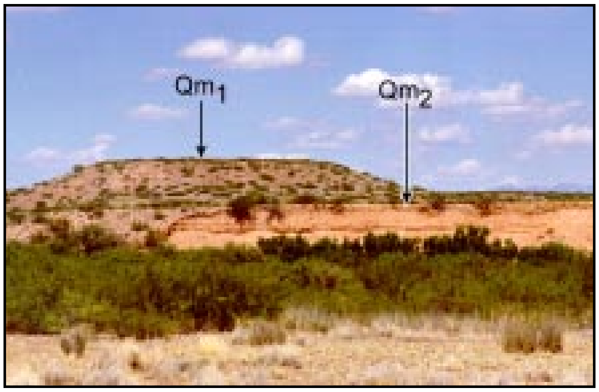

Figure 14. Two middle Pleistocene surfaces preserved along Hay Hollow Wash, Lazy J Ranch quadrangle. Bench in middle ground is mapped as Qm_2, whereas bench in background is an older Qm_1 alluvial fan. Gray fine grained surface in foreground is Holocene alluvium (Qy).

Figure 15. Roadcut exposure of middle Pleistocene (Qm_1) alluvial fan along Geronimo Trail, Lazy J Ranch quadrangle. Deposits are moderately indurated mixture of fluvial conglomerates and paleosols (note carbonate accumulation).

older valley fill sediments. Originally, these alluvial fan deposits probably covered extensive areas of the San Bernardino Valley. Surfaces are planar to moderately rounded. Surface clasts commonly exhibit a moderate rusty orange varnish. Chips of caliche are common on surfaces and well-developed petrocalcic horizons are exposed in cut-bank exposures (Figure 15). The average clast size in $\mathbf{Qm_1}$ is often larger than in the underlying basin-fill deposits.

$\mathbf{Qm_2}$ These alluvial fan deposits were also fairly extensive prior to Late Pleistocene - Holocene erosion. Although the deposits look very similar to the older $\mathbf{Qm_1}$, they occupy a lower topographic position and may have slightly less carbonate accumulation. In some areas (e.g., along Silver Creek and Black Draw), these deposits appear to be interbedded with valley basalt flows.

Qmi, $\mathbf{Qm_{1i}}$, $\mathbf{Qm_{2i}}$ Alluvial fan deposits similar to **Qm**, $\mathbf{Qm_1}$, or $\mathbf{Qm_2}$ that were deposited as a thin veneer of material on older basalt lava flows. Soils tend to be somewhat darker orange-brown than typical **Qm**. These surfaces are difficult to distinguish from weathered lava flow surfaces, as only scattered non-basaltic clasts indicate alluvial origin (Figure 16, compare with Figure 9), but they can be recognized from aerial photographs.

Qmo Middle and Early Pleistocene alluvium, undivided. These light-colored deposits occupy topographic positions intermediate between the middle Pleistocene **Qm** and the Pliocene-early Pleistocene **TQo**. In the southern portion of the study area (West of Guadalupe Canyon quadrangle), the deposits are dominated by rhyolite-derived gravels which overlie limestone-dominated older sediments.

TQo Basin-fill deposits (Pliocene to Early Pleistocene) (750 ka to 2 Ma). This unit is composed of fine grained sandstone and siltstone with lenses and pods of moderately to poorly sorted indurated conglomerate, argillic paleosols, and unsorted, unbedded debris flow deposits. Conglomerates consist of rounded to subangular clasts of welded tuff, rhyolite, dacite, white to red chalcedony, limestone, sand-stone, quartzite, and basalt in a light brown sandy to silty matrix. Clast compositions vary depending on the bedrock from which they originated. These deposits are very similar to the underlying basin-fill deposits (map unit **Tsy**), except that **TQo** often contains abundant larger clasts (up to 50 cm) that are not common in the older sediments. These larger clasts are typically subrounded to rounded and heavily coated with carbonate. **TQo** deposits are deeply dissected, have well-defined dark red-brown argillic horizons, and well-developed closely spaced gullies (Figure 17). These features make the unit very distinctive on aerial photographs. In most areas the deposits are mantled with thin lag gravels which

Figure 16. A thin veneer of middle Pleistocene (Qmi) alluvium covers an older basalt flow surface (F4003) along the Geronimo Trail, San Bernardino Ranch quadrangle. The soil is similar to that developed on basalt flow surfaces. The rock fragments that litter the surface are a mixture of subangular to angular basalt and non-basalt rock material. Compare with Figures 7 and 9.

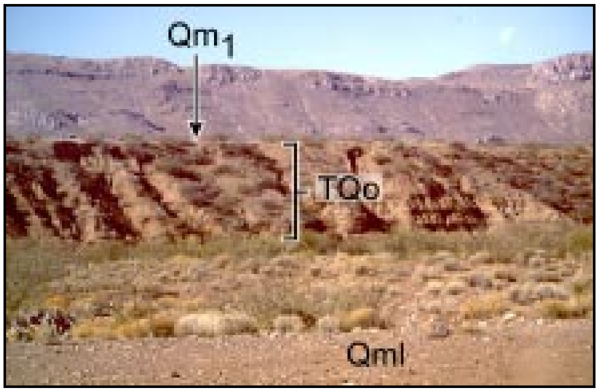

Figure 17. Exposures of Pliocene to early Pleistocene (TQo) basin-fill deposits along Silver Creek, with Perilla Mountains in background. TQo deposits are well-indurated alluvial fans and fluvial deposits incised by closely spaced gullies. The deposits are frequently capped by thin deposits of middle Pleistocene (Qm_1) sediments, which often form a lag gravel drape over the older TQo deposits.

obscure almost every exposure but they are well exposed in the deeply incised drainages in the southern and western portions of the study area.

Tsy Older Basin-fill deposits. These deposits are composed of interbedded fine-grained, tan siltstones, thin sandstones, and conglomerates typical of braided stream deposits. The beds have a slight dip (3^o-7^o), but it is uncertain if this represents primary deposition or later deformation. On the west side of the Guadalupe Canyon quadrangle, the sandstone and conglomerate beds contain dominantly clasts of felsic volcanic rocks (mostly welded tuff, with minor rhyolite and dacite), and very minor basalt. On the west side of the Guadalupe Spring quadrangle, the deposits contain mostly limestone clasts moderately to strongly cemented with carbonate. In all areas most clasts are subrounded and rarely larger than 20 cm across. Silty beds are light tan and erode easily. **Tsy** is difficult to distinguish from **TQo** in the central and western areas of the study area.

Tas Oldest Basin-fill deposits (Miocene). These rocks are composed of interbedded, moderately consolidated red sandstones and conglomerates. The conglomerates contain angular to rounded andesite clasts up to 15 cms in a red sandy matrix; clasts of dacite and welded tuff are present in some exposures. The unit is exposed only in the southwestern corner of the study area (San Bernardino Ranch and East of Douglas quadrangles). Typically these sediments dip 10^o to 28^o to the west-southwest and are conformable with underlying andesite lavas (Ta). These sediments were deformed by basin-and-range faulting and are unconformably overlain by undeformed **TQbf** lavas and Quaternary alluvial deposits.

BASALTIC ROCK UNITS

Numerous basalt volcanoes and their associated lava flows and pyroclastic deposits are present in the San Bernardino Valley. Relative ages of some of the flows and cones can be inferred from superposition and degree of surface weathering. Detailed mapping allowed us to differentiate several lithologic units on the cones based on the dominant rock type (Figure 18). These units include cinders (Qbpc), vent lavas (Qbvl), agglomerate breccias (Qbpb), basaltic intrusive dikes (Qbi), basaltic tuffs (Qbpt), and polylithic surge tuff-rings (Qps) associated with phreatic eruptions. Older lavas are exposed along the mountainous flanks of the valley and are probably present in the subsurface of the valley.

Qbp Basaltic pyroclastic deposits, undifferentiated (Pleistocene). This unit includes basaltic materials that accumulated proximal to vents and formed the cones at each eruption site. Typically, the rocks are dark gray to dark reddish brown, often oxidized to rusty brown, scoriaceous, deposits that include abundant cinders, blocks, bombs, and agglutinate. Surfaces range from gentle to steep slopes with variable cover of very angular boulders and cinders interspersed with outcrops of lava or indurated cinders or breccia. Where possible, **Qbp** is subdivided into predominant facies, including:

Qbvl Basaltic vent lava and agglutinate – Dark gray to dark reddish brown lava flows (often rootless) and splatter, typically highly vesicular and variably oxidized; the amount of pyroclastic material varies, but is generally much less than 50%. Some cones are composed mostly of **Qbvl**: V3003b is

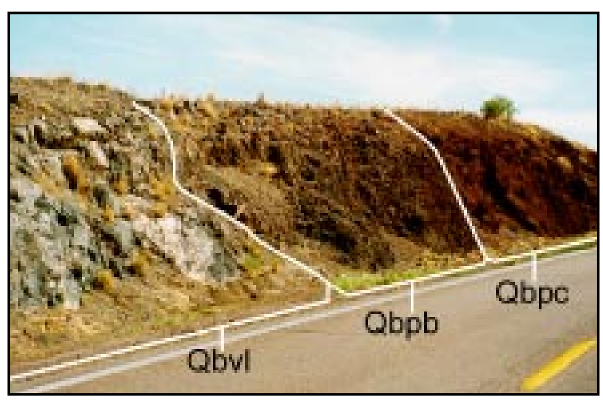

Figure 18. "Typical" basalt volcano cone stratigraphy is exposed in a road cut along Highway 80, Pedregosa Mountains East quadrangle (cone V2009). Dark gray-brown vent lava (Qbvl) is on the left, massive reddish-brown agglomerate (Qbpb) forms the center of the outcrop, and brownish-red indurated cinder (Qbpc) forms the right (north) end of the roadcut. The rock facies are not usually so well-defined on any given cone.

Figure 19. Massive ledges of welded bedded cinders (Qbpc) on the western crest of V1133, center of the Paramore Crater quadrangle. Average pyroclast size is 2-64 mm, although a few larger bombs are present.

an example of an agglutinate cone totally rimmed with lherzolite-bearing lava.

Qbpc Basaltic cinder deposits – Proximal vent facies pyroclastic material that consists of dominantly (>50%) scoriaceous lapilli-sized pyroclasts (2 to 64 mm). This unit typically forms cindery debris aprons on the slopes of cones and is gradational with **Qcb**. Where exposed in cross section the cinders are commonly bedded (Figure 19). Locally the cinder deposits may be welded, forming resistant ledges (e.g., V1025a, V1133) that may be gradational with and difficult to distinguish from **Qbpb**.

Qbpb Basaltic agglomerate – Proximal vent facies pyroclastic material that consists of dominantly (>50%) block- and bomb-sized pyroclasts (>64 mm). Forms rubbly debris on slopes of cones and, locally, indurated cliffs (e.g., northwest inner rim of V3003a, Figure 20). May be difficult to distinguish from **Qbpc**.

Qps Pyroclastic surge deposits – Light to medium gray tuff and lapilli tuff deposits around phreatic explosion craters (see Figure 4). The unit includes lateral pyroclastic flow, collapse, and air-fall deposits. Typical exposures are massive to thinly bedded to laminated, matrix-supported aggregates of millimeter to boulder-sized (average size is <64 mm) rock fragments and broken crystals in a clay-rich to coarse-grained sandstone matrix. Clasts are subangular to subrounded, poorly sorted, and are dominantly Tertiary volcanic and pre-Tertiary sedimentary rocks with lesser amounts of basaltic material. Crude fining-upward sequences are present, and planar and low-amplitude bedforms are locally abundant, with bomb sags present in some deposits. May be locally reworked. At least eight phreatic craters have been recognized in the study area, with the best exposures of surge deposits around V3003a, V1135 (Paramore Crater, Figures 3, 5), and V2022b.

Qbpt Basaltic tuff – Proximal vent facies pyroclastic material that consists of dominantly (>50%) tuff-sized basaltic pyroclasts (<2 mm) and broken crystals in an olive green to olive brown sandy devitrified matrix of basaltic ash. Usually poorly exposed in limited outcrops (e.g., V1119a) due to erosion and colluvial cover (see Figure 12).

Qbf Basalt lava (Pleistocene). Basalt lavas erupted as thin, low viscosity flows from many of the volcanoes in San

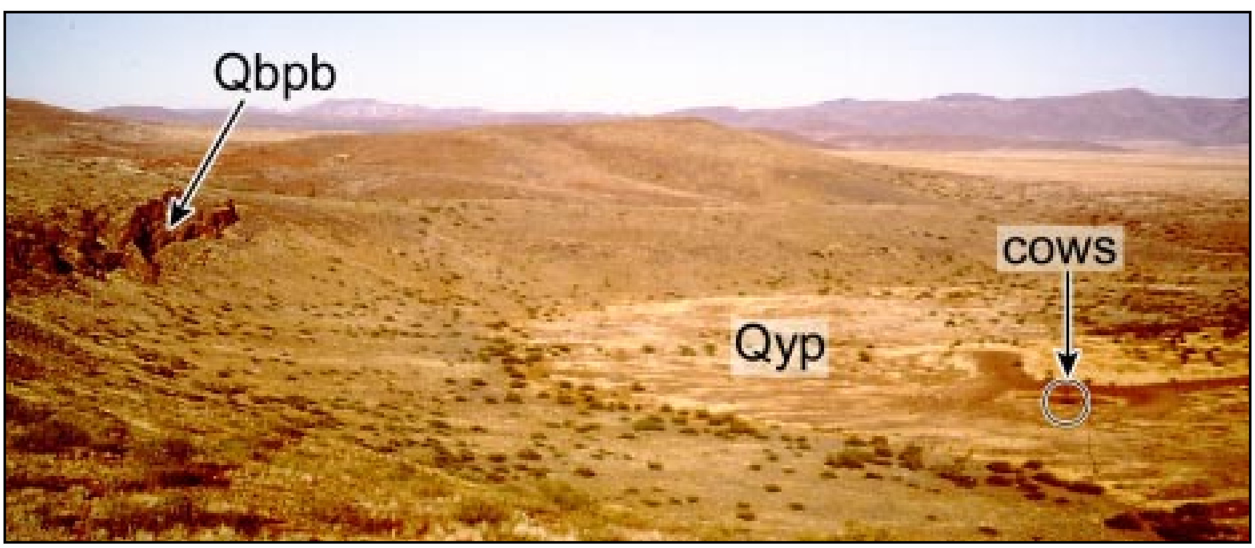

Figure 20. View of maar crater V3003a on the Cinder Hill quadrangle: massive cliffs of indurated basaltic agglomerate (Qbpb) form the northwestern margin of this 1 km diameter crater. Holocene playa deposits (Qyp) cover the floor of the maar (cows for scale).

Bernardino Valley and form a series of overlapping flows ranging from <5 up to 10 meters thick (see Figures 2 and 10). Flow surfaces are gently sloping and planar with scattered basalt cobbles and boulders, to undulatory or hummocky surfaces covered with abundant basalt boulders and cobbles (see Figures 6, 7). Interiors of flows are massive and columnar jointing is common where exposed in cross section. Soils developed on flow surfaces are chocolate brown smectitic vertisols of variable thicknesses. The basalts range from fine grained to aphyric to microporphyritic and contain up to 3% anhedral to subhedral phenocrysts (up to 3 mm) of olivine, plagioclase, and minor pyroxene. Groundmass textures are holocrystalline to aphanitic and are locally trachytic. Olivine is relatively fresh or slightly yellow, but in places the crystals have altered to red opaques (iddingsite). The rock is commonly vesicular, and vesicles are typically open, rounded to flattened, and locally lined or filled with calcite. Many, if not all, flows contain subrounded to well-rounded xenoliths ranging in size from a few millimeters to more than 40 cm in diameter. Ultramafic xenoliths are common and include lherzolite, dunite, pyroxenite, and other lithologies derived from the mantle (Figure 21) (Kempton and Dungan, 1989; Kempton et al., 1990; Kempton et al., 1984b). Crustal xenoliths include Tertiary silicic volcanic rocks, Paleozoic sedimentary rocks, and fragments of granite and gneiss. Black, glassy, subhedral xenocrysts of pyroxene, spinel, and amphibole (kearsutite), up to 4 cm long, and light gray to white, translucent xenocrysts of anhedral to subhedral plagioclase and anorthoclase (?) up to 5 cm across are also common (see Kempton et al, 1982 and 1984 for details).

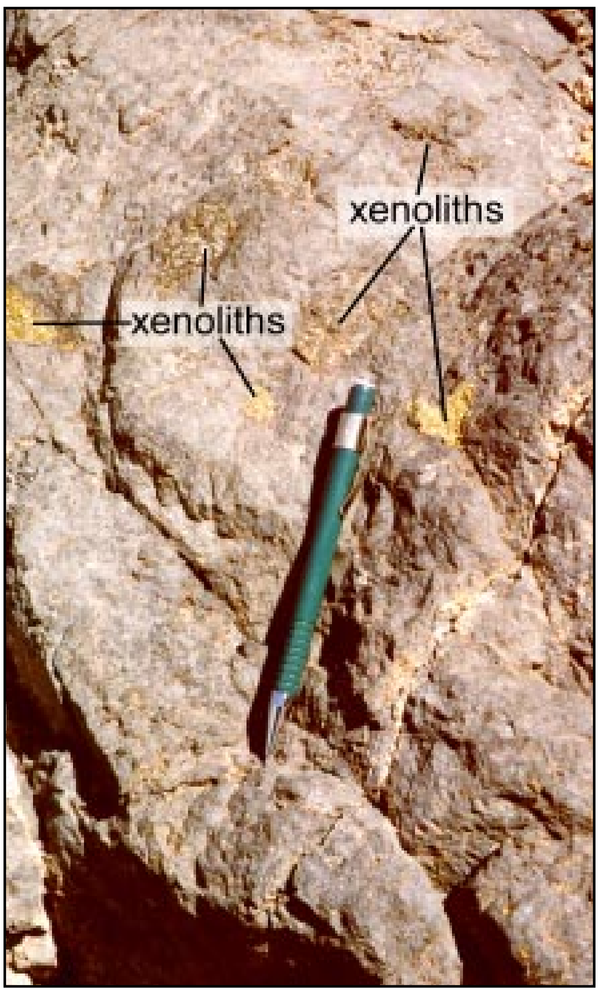

Figure 21. Xenoliths (including lherzolite and pyroxenite) and megacrysts are abundant in some flows and vent lavas from the San Bernardino volcanic field. Xenoliths up to 0.5 meters have been found, and up to 20 cms are not uncommon.

TQbf Basalt. Contains anhedral to subhedral phenocrysts of olivine, mostly altered to red opaques, in a dark gray aphanitic to trachytic matrix. These basalts are mineralogically very similar to the younger basalts that cover the valley floor (map unit **Qbf**). **TQbf** basalts are typically fine-grained or aphyric to locally microporphyritic, with plagioclase and olivine phenocrysts; they also contain abundant xenocrysts of black, glassy pyroxene, spinel, and amphibole. Light gray to white translucent xenocrysts of subhedral plagioclase or anothoclase (?) up to about 2 cm long (see Kempton et al, 1982 and 1984 for details) are also present. However, these basalts contain only rare lower-crustal xenoliths. The slightly vesicular Krentz Ranch flow (1.48 $\pm$0.02 Ma) exhibits crude vertical columnar joints with variable sub-horizontal platy joints.

Tb Older Basalt. Contains anhedral to subhedral phenocrysts of olivine, mostly altered to red opaques, in a dark gray aphanitic to trachytic matrix. These basalts are mineralogically very similar to the younger basalts covering the valley floor to the west (map unit Qbf). **Tb** basalts also contain abundant xenocrysts of black, glassy pyroxene and spinel and translucent subhedral plagioclase up to about 2 cm long. However, these basalts contain only rare lower-crustal xenoliths. In exposures along Sycamore Creek, the unit is interbedded with conglomerate (only locally mapped separately as **Tc**). This unit forms stacks of multiple flows several hundred feet thick on the western side of the Peloncillo Mountains. The flows are nearly horizontal and only slightly tilted locally. In the Skeleton Canyon quadrangle, the unit is offset by normal faults down-to-the east. Small exposures on the eastern side of the range suggest the basalt flows may have been more extensive before erosion. One small exposure of basalt about 1 mile north of Bunk Robinson Peak appears to be interbedded with welded-tuff breccia (map unit **Ttx**).

Tc Conglomerate. This unit is interbedded with basalt (map unit **Tb**). Exposures between Sycamore Creek and Cottonwood Creek contain rounded cobbles to boulders of light gray welded tuff, limestone, dacite, and basalt, all in a tan to red silty to sandy matrix weakly to moderately cemented with calcium carbonate.

TERTIARY BEDROCK UNITS

Tru Undifferentiated rhyolite units (Miocene - Oligocene). This unit includes rhyolitic extrusive and intrusive rocks in the Pedregosa (including the Rhyolite of Joe Glenn Ranch (Drewes and Brooks, 1988) dated 30.4 ±3.0 m.y.) and Perilla Mountains on the western and northwestern margins of the study area. Ash-flow tuffs, dikes, and related volcanoclastic deposits are included.

Tr Rhyolite of Clanton Draw (Oligocene). This unit is composed of many separate, crystal-poor rhyolite flows that commonly exhibit contorted flow-banding. Most exposures are light gray and contain very small subhedral phenocrysts of quartz, biotite, and clear-gray feldspar resembling sanidine. Phenocrysts are typically less than 1 mm wide and comprise 1-5% of individual flows. Many flows have a vitric base that commonly stands out as a dark band (locally mapped at the base of the unit). Interbedded light yellow lithic tuffs several meters thick are common, but appear to pinch out rapidly along strike. Good exposures of individual flows with interbedded tuffs and vitric layers can be seen in section 35, T. 21 S., R. 32 E., and south of Clanton Draw in the southeast corner of the Skeleton Canyon quadrangle. Erb (1979) named the unit and reported a zircon fission-track age of 25.8 ± 1.2 Ma for this unit.

Ttr Welded tuff (Oligocene). This crystal-poor welded tuff contains very few subhedral phenocrysts of quartz, sanidine, and biotite (about 1% of rock) less than 1 mm wide. Pumice fragments are very flattened and resemble thin laminae from edge-on. Outcrops are dark tan and the rock breaks into platy fragments. Near the head of Whitmire Canyon the base of the unit is non-welded and light gray. Erb (1979) originally described this rock as the tuff of Whitmire Canyon—the youngest rock in the area. This study has revealed that the tuff is also overlain by rhyolite flows. In the very southeast corner of the Skeleton Canyon quadrangle, a thin tuff bed interbedded with rhyolite contains a crystal-poor densely welded top, and may be the same unit.

Tt Bedded lithic tuffs (Oligocene). These crystal-poor tuffs contain minor subhedral phenocrysts of quartz and biotite in a light yellow, bedded, aphanitic matrix. The rock also contains subangular to subrounded lithic fragments of pumice, rhyolite, and dacite, all commonly 2 to 10 cm across. In outcrops in Section 11, T. 22 S., R. 32 E., and in Section 9, T. 32. S., R. 21 W., the tuffs are strongly welded with flattened pumice clasts. The welded exposures at the head of Whitmire Canyon are clearly interbedded with the rhyolite of Clanton Draw.

Tsc Tuff of Skeleton Canyon (Oligocene). This unit contains abundant phenocrysts (~10% of rock) of clear subhedral to rounded quartz 1-2 mm wide, clear chatoyant sanidine 1-3 mm long, and minor subhedral biotite, all in a medium gray aphanitic matrix. Lenticular, flattened, light gray pumice clasts from 0.5 to 3 cm long are common. Throughout most of the study area no flow-breaks are visible and the rock appears to consist of one cooling unit. Excellent exposures in Skeleton Canyon mantle a steep angular unconformity dipping approximately 60 degrees to the east. This unconformity may represent the margin of a buried cauldron. Also in Skeleton Canyon, the welded tuff is locally overlain and underlain by light gray non-welded tuff, mapped separately as map unit **Tscn**. The light gray pumice clasts contrast sharply with the medium gray matrix and make the tuff of Skeleton Canyon very distinct from all the other welded tuffs in the southern Peloncillo Mountains. The unit is thickest in Skeleton Canyon, where it is associated with a steep unconformity, but it is also very similar to the distinctive Rhyolite Canyon Tuff associated with the Turkey Creek Caldera in the Chiricahua Mountains to the northwest (Drewes, 1982; Du Bray and Pallister, 1991).

Tscn Tuff of Skeleton Canyon, non-welded (Oligocene). This unit is mineralogically the same as the welded tuff of Skeleton Canyon, but forms light gray-colored slopes instead of darker gray cliffs. Pumice clasts are subspherical instead of lenticular. In the northwest corner of the Skeleton Canyon quadrangle, welded tuff is underlain by non-welded tuff locally at least 200 feet thick. In this area, on the west side of the hills in gullies next to the road (where the non-welded tuff is thickest), large spherical accretionary lapilli or “tuff balls” are abundant and weather out into spheres up to 10 cm in diameter.

Tdc Coarse-grained dacite of Outlaw Mountain (Oligocene). This crystal-rich lava contains abundant subhedral phenocrysts of light gray to translucent plagioclase up to 1.5 cm, anhedral biotite up to 5 mm, partially altered to hematite, and less abundant hornblende in a dark purple to dark brown aphanitic matrix. Locally small anhedral quartz is present. Plagioclase crystals are very conspicuous and resemble the plagioclase in both the younger and older basalts (map unit **QTbf** and **Tb**, respectively). Glomeroporphyritic clots of plagioclase are common. This unit is interbedded with autoclastic flow-breccia well-exposed in places along a west-facing cliff forming the central part of the mountain range (Figure 22). Locally contains subrounded xenoliths of very fine-grained holocrystalline rocks 1-15 cm wide that look like they have a similar composition as the dacite. Named by Erb (1979).

Tdm Medium-grained dacite of Outlaw Mountain (Oligocene). This dacite lava is mostly roughly

Figure 22. Multiple Tertiary volcanic units on Outlaw Mountain in the Peloncillo Mountains, as viewed from Cottonwood Draw. Oligocene coarse-grained dacite of Outlaw Mountain (Tdc) forms the top of the mountain, with welded ash-flow tuffs (Ttw) forming the massive cliffs (left). Dacite breccia (Tdx) and monolithic welded tuff breccia (Ttx) forms the slope below Tdc.

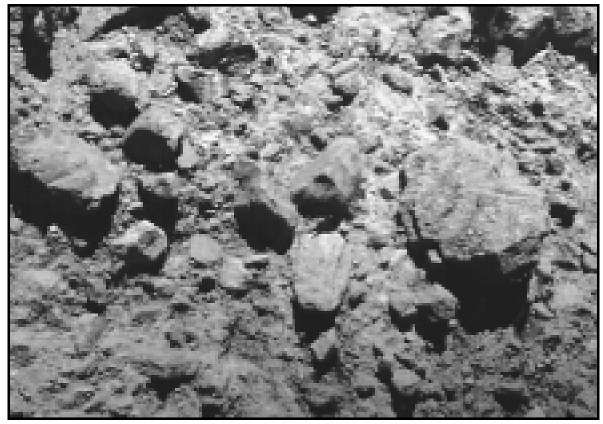

Figure 23. Typical outcrops of dacite breccia (Tdx), in the Peloncillo Mountains east of Outlaw Mountain.

equigranular to slightly porphyritic and contains 1-2 mm wide subhedral phenocrysts of plagioclase, biotite, hornblende and minor quartz in an aphanitic matrix. The rock is purple to tan and commonly has a slightly lighter color than the coarse-grained dacite. No large plagioclase phenocrysts nor inclusions were seen. This lava underlies the coarse-grained dacite of Outlaw Mountain (map unit **Tdc**).

Tco Older conglomerate (Oligocene). One small remarkable exposure of this unit overlies the fault near the center of the Guadalupe Spring quadrangle. This thinly bedded tan-colored conglomeratic sandstone contains clasts of welded tuff and dacite in a sandy matrix. Bedding within the exposure changes from 23 degrees west on the lower portion to 70 degrees west near the top.

Tql Quartz latite (Oligocene). This rock contains subhedral phenocrysts of light gray feldspar (sanidine?) quartz, biotite, hornblende, and minor sphene, all in a light grey aphanitic matrix. Exposures on the north side of Sycamore Creek contain about 15-20% phenocrysts, whereas exposures in Baker Canyon are darker gray green and contain fewer phenocrysts. On the north side of Sycamore Creek in the Guadalupe Spring quadrangle, the contact with the underlying rocks is very sharp and inclined. Locally, there is a 1 to 2 meter thick crystal-poor sandy tuff at the base. The quartz latites form small intrusive bodies. Near Sycamore Canyon it cuts across coarse-grained dacite (map unit **Tdc**) but appears to be overlain by dacite breccia. In the Guadalupe Canyon quadrangle, the unit forms two small intrusions, one of which cross-cuts the Baker Canyon Fault.

Tdx Dacite breccia (Oligocene). This unit coarsens upward from fine-grained conglomeratic sandstone to boulder conglomerate and breccia. It is exposed in the central part of the mountains from Sycamore Creek on the south to about 1 km north of Outlaw Mountain. On the north side of Sycamore Creek the lower portions are composed of fine-grained, tan-colored conglomeratic sandstone that is mostly buried by younger alluvium. Exposures here are best seen in the gullies and stream-cuts. To the north, on the south side of Cottonwood Creek, conglomeratic sandstone is locally interbedded with thin siliceous carbonate layers (marl?) 10 cm or so thick. Upward in the section the unit is dominated by coarse conglomerate. Bedding is medium to thick and is most easily discerned from a distance. Lower in the section, many clasts are welded tuff, but upward almost all the clasts are subrounded to angular dacite. The upper part is locally interbedded with dacite flows and grades upwards locally into non-bedded autoclastic dacite flow-breccia (mapped as part of the dacite lavas) (Figure 23). Near 31^{o} 27' 30", 109^{o} 06' 00" light gray medium-grained dacite clasts are surrounded by a light gray, crystal-rich dacite(?) matrix. It is not clear if it is a flow-breccia or sedimentary breccia. The unit was named by Erb (1979) the breccia of Hog Canyon for excellent exposures there.

Tro Older rhyolite. This rock is a sub-aphyric rhyolite lava and contains small phenocrysts of quartz and rare biotite less than 1 mm across. Spherulites are common. In exposures about 1 mile north of Devils Kitchen, the rhyolite is vitric near the contact with overlying dacite. A light-yellow bedded crystal-poor lithic tuff crops out at and near the base of the unit. The rhyolite is exposed only in the north along Skeleton Canyon, where the rocks weather into steep, light tan slopes with rough, jagged outcrops.

Tax Andesite breccia. This unit is composed almost entirely of dark gray to purple clasts of andesite. It is

Figure 24. Outcrop of the monolithic welded tuff brecca (Ttx) in the Peloncillo Mountains. Bunk Robinson Peak in distance.

exposed in the southern part of the map area in the Guadalupe Spring and Guadalupe Canyon quadrangles. The most extensive exposures are in the Guadalupe Canyon quadrangle where they form dark gray, non-bedded, featureless deposits at least 600 feet thick. Individual clasts range from pebble-size to large boulders and are angular to subrounded surrounded by a sandy andesitic matrix. Where deposits are mixed with welded-tuff breccia they are mapped separately as map unit **Ttax**. About 1.5 to 2 miles south of Bunk Robinson Spring in the Guadalupe Spring quadrangle, dark gray to purple deposits containing pebble- to cobble-size clasts of andesite form dark, subdued slopes beneath and intercalated with welded-tuff breccia. South and southeast of Guadalupe Mountain, the andesite is highly fractured but the fracture/joint orientations are consistent, and the cracks are filled with andesitic sand and carbonate. Nearby exposures are brecciated and jumbled. The exposures with consistent fracture orientations may represent large relatively coherent blocks.

Ttax Mixed breccia. These poorly sorted deposits contain clasts of andesite, dacite, various welded tuff units, and rare limestone and sandstone. Most exposures crop out in the eastern half of the Guadalupe Canyon quadrangle. West and southeast of Guadalupe Canyon these deposits contain discrete zones of andesite and fine-grained crystal-poor welded tuff that has not been recognized elsewhere in the study area. The welded tuff and andesite zones have very irregular, but sharp, contacts and with more detailed work can probably be mapped as distinct units. The crystal-poor welded tuff zones only occur in the southeast corner of the map. In this same area the unit contains very localized accumulations of limestone clasts, ranging in size from cobbles to large boulders (some are located on the map). Abundant pelecypod fossils suggest the limestone clasts were derived from the Bisbee Group.

Ttx Monolithic welded-tuff breccia. This extensive unit is composed of very poorly sorted, angular to subangular sand to large blocks of welded tuff (Figure 24). The individual clasts are rotated with respect to the surrounding clasts such that the primary eutaxitic foliation is almost completely obscured. Spaces between the clasts are surrounded by fine-grained sandy tuff and angular fragments of welded tuff. This unit includes both mesobreccia and megabreccia. One mile southeast of Eicks Spring (on the south side of Sycamore Creek), the unit contains an intact block over 50 meters across. From about Baker Canyon northward, the unit contains almost exclusively clasts of welded tuff. From about Baker Canyon southward, the unit contains about 60% clasts of welded tuff and 40% clasts of andesite and dacite (and very minor limestone). The different rock types occur as discrete lenses and layers. From a distance some of the layers can be discerned as dark- and light-colored bands, but in other areas the different rock types can only be seen up close. The differences are most obvious in the east-central part of the Guadalupe Spring quadrangle where dark-colored bands of andesite can be distinguished from light-colored bands of welded tuff. Near the central part of the range the unit is over 800 feet thick; it erodes into steep, rough, featureless tan-colored hills.

Ttu Upper welded ash-flow tuff. This welded ash-flow tuff unit is crystal-rich and contains 1-5 mm phenocrysts of clear quartz, light gray to almost clear sanidine, and minor biotite. In the northern part of the Skeleton Canyon quadrangle it is composed of two sub-units: a lower, slope-forming unit and an upper cliff-forming unit. Both sub-units are mineralogically similar. The rock forms light gray steep outcrops that contrast with the underlying older welded tuff (map unit **Tto**). On weathered surfaces, the large quartz phenocrysts stand out in relief. In this respect it resembles map unit **Ttw**. In the southern part of the Guadalupe Canyon quadrangle near the international border, another crystal-rich welded tuff overlies an older welded tuff (map unit **Ttw**). It is not clear if the upper tuff (map unit **Ttu**) in the two areas are related or not, but the symbol **Ttu** was used because both overlie a lower welded tuff unit.

Ttun Non-welded ash-flow tuff. This unit is exposed in the southern part of the Guadalupe Canyon quadrangle where it forms light-colored slopes. It underlies the upper welded tuff (map unit **Ttu**), also underlies dacite (map unit **Td**), suggesting it may be the upper part of the lower tuff (map unit **Ttw**).

Ttw Welded ash-flow tuff. This crystal-rich tuff contains phenocrysts of about 15-20% clear, subhedral quartz, 10% sanidine, and 1-2% biotite, all between 1-5 mm across. Biotite is scarce and is partially altered to hematite. Some sanidine is chalky white, but most are clear to light gray. Quartz is abundant and commonly sticks out in relief on weathered surfaces, which gives the rock a rough, slightly coarse-grained appearance. Fresh surfaces are light pink to tan, but the rock weathers tan and is commonly slightly varnished. Where strongly welded, the rock forms cliffs and blocky ledges (see Figure 22). Where less welded, the tuffs erode into light-colored crumbly slopes. Several welded tuff units are interbedded with welded-tuff breccia (map unit **Ttx**) in the southern Peloncillo Mountains. However, they are mineralogically very similar and not distinguished as separate units except where separated by breccia. Erb (1979) reported a zircon fission-track age of 27.1 ± 1.5 Ma for a sample of welded tuff collected along the Geronimo Trail, about ½ mile west of Miller Spring next to Cottonwood Creek. Similar rocks are exposed in the southern end of the Perilla Mountains, in the southwestern corner of the project area (East of Douglas quadrangle) and may be equivalent to the tuffs in the Peloncillo Mountains.

Tto Older welded ash-flow tuff. This welded tuff contains abundant quartz and sanidine and minor biotite, all 1-3 mm across in a dark pink aphanitic matrix. The tuff also contains lithic fragments of welded tuff and dacite. This unit is very similar to the welded tuffs farther to the south (map unit **Ttw**). The unit forms dark colored rounded hills in the far northern part of the Skeleton Canyon quadrangle.

Ta Andesite. This lava contains ~10-15% subhedral phenocrysts of light to medium gray plagioclase and dark gray to gray-green pyroxene, both up to 6 mm across in a purple-gray aphanitic matrix. Pyroxene crystals are often altered to hematite, and plagioclase phenocrysts are commonly chalky white. The lava has been cut by thin siliceous veins, with red- and yellow-colored selvages 10 to 20 cm out from and parallel to the veins. The andesite flows appear to be interbedded with welded tuff (map unit **Ttw**) near the base of the section in the Guadalupe Canyon quadrangle. The rock locally cuts across foliation in the welded tuff, suggesting some exposures may be intrusive. A small body of andesite **(Tai)** intrudes the Bisbee Group in the very southwest corner of the Guadalupe Canyon quadrangle. In the east-central part of the Guadalupe Spring quadrangle, this unit is locally transitional between flow and breccia, which are mapped as **Tax**. Similar andesites are exposed in the southwestern corner of the project and are assumed to be equivalent.

Tfi Felsic hypabyssal dikes. This light tan rock contains 1-3 mm phenocrysts of mostly clear quartz, minor sanadine, and rare biotite, all in a tan aphanitic matrix. It also contains what appear to be small pumice fragments less than about 2 cm across. The unit has sharp irregular contacts within both the chert conglomerate (map unit **Kcc**) and the limestone conglomerate (map unit **Kcl**) of the Bisbee Group, suggesting the rock is intrusive, although it may be interbedded. The mineralogy is similar to the ash-flow tuff unit (map unit **Ttw**) and may have been small vents.

PALEOZOIC AND MESOZOIC BEDROCK UNITS

Cretaceous Units

Kb Bisbee Group, undivided. The sedimentary rocks of the Bisbee Group form ledges on steep, rounded hills in the southeast part of the study area and in the Pedregosa and Perilla mountains. The group contains thin to medium bedded, light gray to blue-gray limestones interbedded with light tan, pink, and gray fine-grained sandstones and limy sandstones. Locally, limestone beds contain very abundant fossil pelecypods (*graphaea*) up to 10 cm long, and the limy sandstones are particularly fossiliferous. The limestone and sandstone beds are difficult to distinguish from a distance. The Bisbee Group in the area is folded and several faults are identified. In the Pedregosa and Perilla mountains, the Bisbee Group rocks were not mapped separately for this report, but the Cintura, Mural, Morita, and Glance Conglomerate formations have been identified by other investigators (Drewes and Brooks, 1988). The three lower formations of the Bisbee Group are recognized in the southeastern portion of the study area:

Kl Lowell Formation. Only the upper portion of this unit is exposed in the study area, where a reconnaissance measured section shows it is composed of yellowish brown to gray bioclastic and pelecypod-rich limestones with interbedded reddish brown cross-bedded sandstones (Dirks, 1966). Local masses of coral are also present (Kelly, 1966).

Km Morita Formation. This unit contains mostly red-brown to dark purple siltstone interbedded with thin sandstone layers 10-50 cm thick. The siltstone erodes easily into slopes and the sandstone erodes into small resistant ledges. The upper contact is gradational. The upper part of the unit contains more abundant interbedded limestone layers.

Kc Glance Conglomerate, undivided. Two informal members of the Glance Conglomerate are recognized in the southeastern part of the study area:

Kcl Limestone conglomerate. This sub-unit of the Glance Conglomerate overlies the cherty conglomerate (map unit **Kcc**) and contains subrounded to well-rounded clasts of limestone, 2 to 15 cm in diameter, in a moderately to well-cemented calcium carbonate matrix. Upper and lower contacts are sharp. The unit forms a rounded, cobble-covered ridge between the underlying cherty conglomerate and the subdued slopes of the overlying fine sandstones and siltstones of the Morita Formation.

Kcc Cherty conglomerate. The basal conglomerate of the Bisbee Group contains subangular to well-rounded clasts of light to dark gray and tan chert, quartzite, and sandstone, all in a red sandy matrix. Clasts range in size from about 2 to 10 cm, but larger clasts are up to 20 cm across and are rounded to well-rounded. Smaller clasts are more angular. Most clasts are stained red. This unit unconformably overlies the Paleozoic rocks of the study area.

Paleozoic Units

Pe Epitaph Dolomite. Fresh surfaces are red-black to dark gray. On weathered surfaces the rock is light to medium gray to pale brown and typically very rough. Beds are typically 1-2 feet thick, but are locally as thick as 6-10 feet. Breccias and conglomerates containing pebble-size clasts occur throughout the formation. Outcrops are highly fractured and commonly permeated by abundant, small light gray calcite veins. Locally, the unit contains abundant dark red-brown irregularly shaped chert nodules less than 5 cm across. In the study area, the unit is bounded by a thrust fault at the base and an erosional unconformity at the top. The Epitaph Dolomite is about 800 feet thick (Kelly, 1966).

Pc Colina Limestone. This limestone weathers light bluish gray to medium gray, but on a fresh surface it is dark gray to black. The lower portion contains abundant fossils of crinoids, echinoids, gastropods, and brachiopods. Beds are typically 2-4 feet thick. The formation can be recognized from a distance both by its ledge-forming outcrops and by its blue-gray color, which contrasts with the red siltstones of the underlying Earp Formation and with the brown dolomites of the overlying Epitaph Dolomite (Kelly, 1966).

P^{3}e-P^{3}eh Earp Formation and Horquillah Limestone. From oldest to youngest the Earp includes limestone, gray-orange pebble conglomerate up to 90 feet thick, a thick sequence of red to orange siltstone and calcarenite, and limestone, yellow dolomite, and brown cherty dolomite (see Kelly, 1966 for a more detailed description). The limestones at the base of the Earp Formation contain abundant fusulinids (probably *Triticites*), and less abundant echinoid spines and plates, and crinoid stems. The Horquillah Limestone is composed of thin- to thick-bedded cherty gray limestone with thin interbeds of calcareous shale or siltstone. In the study area, the units are at least 380 feet thick, but exposures are limited. The conformable contact with the overlying Colina Limestone is sharp. Three isolated outcrops of the Earp-Horquillah limestones are located 2-3 kms south of Paramore Crater (see Figure 3) forming inselbergs surrounded by basalt flows that cover the buried pediment. Several adjacent areas of carbonate-rich, light-colored soils, which are clearly not derived from basalt or alluvium, are probably deeply eroded limestone inselbergs.

Undifferentiated Bedrock

MPz Mesozoic and Paleozoic bedrock undifferentiated. Areas of bedrock outcrops identified from aerial photography or cursory field reconnaissance but not mapped or studied in detail. Also includes generalized map units compiled from published sources. Units may include Concha Limestone, Scherrer Formation, Epitaph Dolomite, Colina Limestone (all Permian), Horquilla Limestone (Pennsylvanian), Paradise and Escabrosa Limestones (Mississippian), Portal Formation (Devonian), El Paso Formation (Ordovician), and Bolsa Quartzite (Cambrian) in the Pedregosa Mountains (Drewes and Brooks, 1988) and other margins of the study area.

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