Geologic Map of the Chisos Mountains, Big Bend National Park, Texas

By Robert G. Bohannon

Prepared in cooperation with the U.S. National Park Service

Scientific Investigations Map 3140

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U.S. Department of the Interior
U.S. Geological Survey

View of the high Chisos Mountains looking northeast from Castalon Road. Ward Mountain is to the right above low cloud layer. The Window is the steep-walled canyon in the left center.

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Introduction

This report describes the geology of the Chisos Mountains in the central part of Big Bend National Park, Brewster County, Texas (fig. 1). The compilation summarizes and integrates new geologic mapping and stratigraphic studies with various topical studies and geologic maps that were published between the late 1960's and 2006 (for example, Maxwell and others, 1967; Maxwell, 1968; Muehlberger, 1989; Muehlberger and Dickerson, 1989; Dickerson and Muehlberger, 1994; Barker and others, 1986; and White and others, 2006).

The purpose of the work is to summarize the geology of the Chisos Mountains, one of the most highly visited areas in Big Bend National Park. Although a geologic map of an earlier vintage exists (Maxwell, 1968), the new map included in this report displays the geology in far greater detail at 1:50,000 scale, and it is plotted on a scale-stable, geo-registered base keyed to a modern grid based on the WGS-84, UTM-zone-13 coordinate system. This map and report are also designed to serve as detailed extensions of the contemporary regional geologic map of the entire Big Bend National Park at 1:75,000 scale that is in production by the U.S. Geological Survey (USGS) as of this writing.

Acknowledgments, Mapping Sources, and Methods

This map was produced under the partial auspices of the United States National Park Service (USNPS). Cartography for roads and trails was provided by GIS specialists at the USNPS Park Headquarters in Big Bend. The geologic data come from a variety of sources and the map represents the work of several geologists from the U.S. Geological Survey (USGS), University of Texas at Austin (UTA), and Texas Tech University (TTU). All of the geology as presented is primarily based on the author's interpretation of ortho-rectified USGS color-infrared photogrammetry, which facilitated a uniform horizontal accuracy of geologic features to within 2 m throughout the mapped area. The small map included on the plate shows the areas where the author extensively field-checked the geology during the fall, winter, and spring months of 2003–2007. Large parts of the map also benefited from field studies conducted by several other USGS geologists including Robert Scott, Lawrence Snee, and Kenzie Turner (see plate). Tom Lehman (UTA and TTU) and Ric Page (USGS) conducted regional studies of the Cretaceous and lower Paleogene deposits throughout Big Bend National Park, and all deposits of that age that are shown on this map follow their designations. The surficial deposits (rocks of Quaternary age) of Big Bend has been studied to various degrees by Margaret Berry and Van Williams (Berry and Williams, 2008) and this map reflects their work. Dan Miggins (USGS and University of Texas at El Paso) provided age and petrographic data for specific sites over much of the area.

Geologic Setting

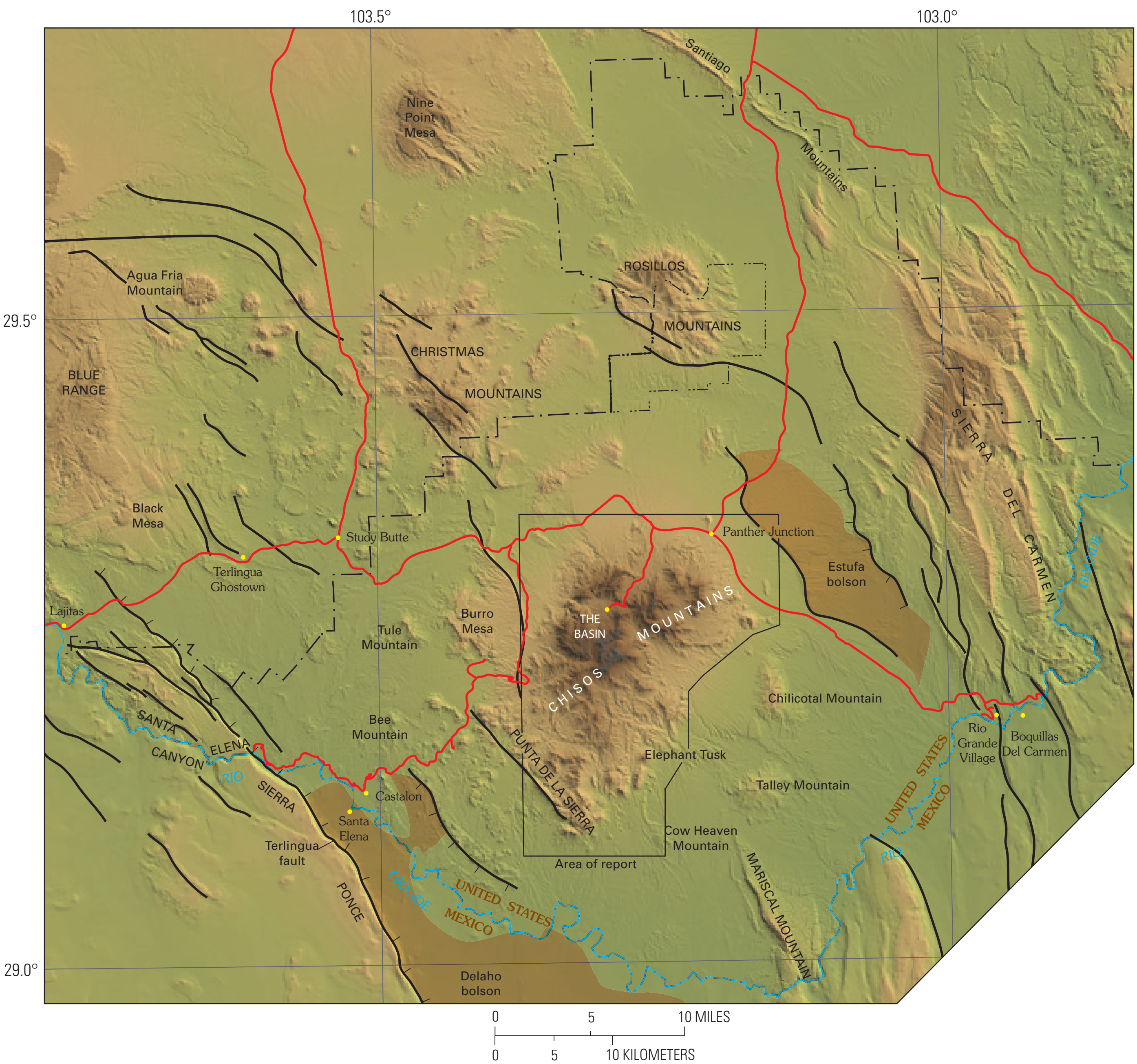
The Chisos Mountains (fig. 2) form some of the highest ground in Texas, second only to Guadalupe Peak near the New Mexico border. The northern half of the range is mostly above 5,500 feet with Emory Peak the high point at 7,825 feet. The mountains are centrally located in Big Bend National Park between Panther Junction and Punta de la Sierra (fig. 2).

Big Bend National Park lies near the diffuse border between the Great Plains Province to the northeast and the Sonoran section of the Basin-and-Range structural province to the west and southwest (fig. 1). These geologically unique regions are distinguished from one another by large differences in their landscape and by the amount and style of internal structural deformation. The Great Plains Province is characterized by flat-lying or gently dipping sedimentary strata, low topographic relief, shallow stream valleys, and by a general lack of faulting. Very little active deposition is occurring on the plains, except in the bottoms of active stream valleys. In southwestern Texas the plains stand at average elevations of 2,000 to 3,300 feet and slope gently east toward the Mississippi River and the Gulf of Mexico. The


114°
112°
110°
108°
106°
104°
102°
34°
32°
30°
28°
26°
Colorado Plateaus
Mogollon Datil volcanic fields
ARIZONA
NEW MEXICO
Southern Great Plains
Rio Grande Rift
Guadalupe Peak
Basin and Range
TEXAS
Trans Pecos volcanic fields
Laramide deformation
Laramide deformation
SONORA
Sierra Madre Occidental
CHIHUAHUA
BIG BEND NATIONAL PARK
Chisos Mountains
GULF OF CALIFORNIA
BAJA CALIFORNIA NORTE
BAJA CALIFORNIA SUR
PACIFIC OCEAN
COAHUILA DE ZARAGOZA
0 25 50 75 100 125 MILES
0 50 100 150 KILOMETERS

Figure 1 (facing page). Generalized map showing the location of Big Bend National Park (darker green area) relative to main tectonic and volcanic features of the southwestern United States and northwestern Mexico. Largest volcanic fields are shown with black stippled pattern. Trans-Pecos fields are widespread in west Texas and cross the Rio Grande into Mexico. Purple regions are affected by Laramide compressional deformation. Basin-and-Range structural province extends throughout southwest Arizona, southern New Mexico, Sonora, and Chihuahua. It includes the Rio Grande rift. Topography is color-graded from lowlands in pale green to highlands in pale brown.

Figure 2 (below). Generalized map of Big Bend National Park, shown by black dotted border. Some of the larger faults that developed during the basin-and-range extensional period are shown with gray lines. The deepest parts of Estufa and Delaho bolsons (where some remnants of the original graben fill are preserved) are shown as yellow-brown areas. Topography is color-graded from lowlands in green to highlands in dark brown, giving a good sense of the height and extent of the Chisos Mountains. Paved highways are shown in red.



Great Plains have remained relatively unchanged for the last 65 million years, except that they have been uplifted to their present height from lower elevations probably in the last 5 million years. The Basin-and-Range province is characterized by linear parallel mountain ranges, deep sediment-filled valleys, and high structural and topographic relief. The eastern part of the province is at a slightly higher average elevation than the plains (fig. 1). The province is known for its complex patterns of Cenozoic faulting. Today it bears little resemblance to the way it was during the Paleocene when the entire Trans-Pecos region was a simple lowland that was near or slightly below sea level.

The geologic history of Big Bend National Park has been punctuated by several distinct episodes of deformation, sediment aggradation, volcanic eruption and intrusion, and denudation.

1) There were numerous deformational episodes between the Neoproterozoic and the end of the Permian. Evidence for some of these events is present in the Paleozoic strata exposed in the northern part of Big Bend National Park (Muehlberger and Dickerson, 1989), but all the rocks old enough to be deformed by these events lie buried by younger deposits in most other places, including the Chisos Mountains and they are not discussed further in this report.

2) The Paleocene and Cretaceous was a time when thick shallow-water marine and coastal sediments were deposited within and on the edges of an interior seaway system that was widespread in many parts of southwest Texas, northern Mexico, central New Mexico, and the Rocky Mountains (RMAG, 1972, Lehman, 1991). The seaway deposits are the oldest rocks exposed in the Chisos Mountains.

3) The Cretaceous and Paleocene rocks were folded and faulted during the Laramide orogeny throughout Trans-Pecos Texas (Muehlberger, 1989; Muehlberger and Dickerson, 1989; Lehman, 1991). The Laramide ended at about 46–47 Ma in the trans-Pecos region (Harlan and others, 1995). Lehman (1991) described the local deposits associated with the Laramide orogeny, but none of these are present in the Chisos Mountains.

4) The end of Laramide folding corresponded to the beginning of a prolonged influx of volcaniclastic sediment and lava flows in the Chisos Mountain region that continued through the remainder of the Eocene into the early Oligocene. I call this the Chisos episode, named after the Chisos Formation of Maxwell and others (1967). The source of the volcanic material has not been identified.

5) A relatively short, but intense episode of local volcanism began at 32–33 Ma in the Chisos Mountains and lasted a few million years at the longest. Several large intrusive and eruptive centers as well as widespread flows are preserved in the range. I refer to this simply as the eruptive and intrusive episode.

6) Big Bend National Park encompasses at least two large grabens, known as the Estufa and Delaho bolsons that formed during the Miocene Basin-and-Range extension. Although no deposits are preserved in the Chisos Mountains, remnants of the graben fill have been described from either side of the range (Dickerson and Muehlberger, 1994).

7) Big Bend National Park has been the site of regional denudation since the introduction of the Rio Grande around the end of the Miocene. Short, local events of sediment aggradation occurred amid considerable regional downcutting and erosion resulting in a broad spectrum of different surficial deposits preserved throughout the Chisos Mountains. This was the denudational episode.

Chisos Mountains Geology

Most geographic locations mentioned in the following discussion can be found on figure 3. Figure 4 is a diagrammatic summary of the most widespread stratigraphic units present in the Chisos Mountains.

Seaway Deposits

The deposits of the seaway and associated coastal plains that are exposed in the parts of the Chisos Mountains described in this report include marine limestone of the Cenomanian to lower Coniacian Boquillas Formation (Kb); marine shale of the late Coniacian and Santonian Pen Formation (Kp); marine shale and fluvial sand of the Campanian and Maastrichtian Aguja Formation (Kag); fluvial, lacustrine, and overbank mudstone and sandstone of the Maastrichtian Javelina Formation (Kj); and fluvial sandstone of the Maastrichtian and Paleocene Black Peaks Formation (TKbp). Cretaceous and Paleocene beds are mostly exposed around the periphery of the Chisos Mountains south of Punta de la Sierra, and north and west of Ash Spring and Ward Mountain. Some are also exposed high in the range near The Basin and in the core of a small structural dome near Tortuga Mountain.

Seaway and related deposits once covered the entire area in a thick sheet as the Big Bend region slowly subsided at about the same rate that sediment accumulated, allowing the land surface to remain near sea level for a long time period. At times the area fluctuated between being just below or slightly above sea level, but overall the area went from shallow marine to lowland nonmarine with time. This offers evidence that the influx of sediment eventually overwhelmed and filled the slowly sinking basin.

The best example of marine deposits left in the Chisos Mountains are the thin-bedded limestone, chalk, and marl of the Boquillas Formation (Kb) in The Basin and Laguna Meadow areas. Nautilus, ammonites, fish (including sharks), and marine reptiles once thrived in the waters while these beds were forming (Maxwell and others, 1967).

Remnants of claystone and fine-grained sandstone of the Pen Formation (Kp) overlie the marine limestone west of Emory Peak and in the core of the anticline near Cow Heaven Mountain (see fig. 2 for location). Most likely a large river system, draining a wide area of land nearby, dumped its

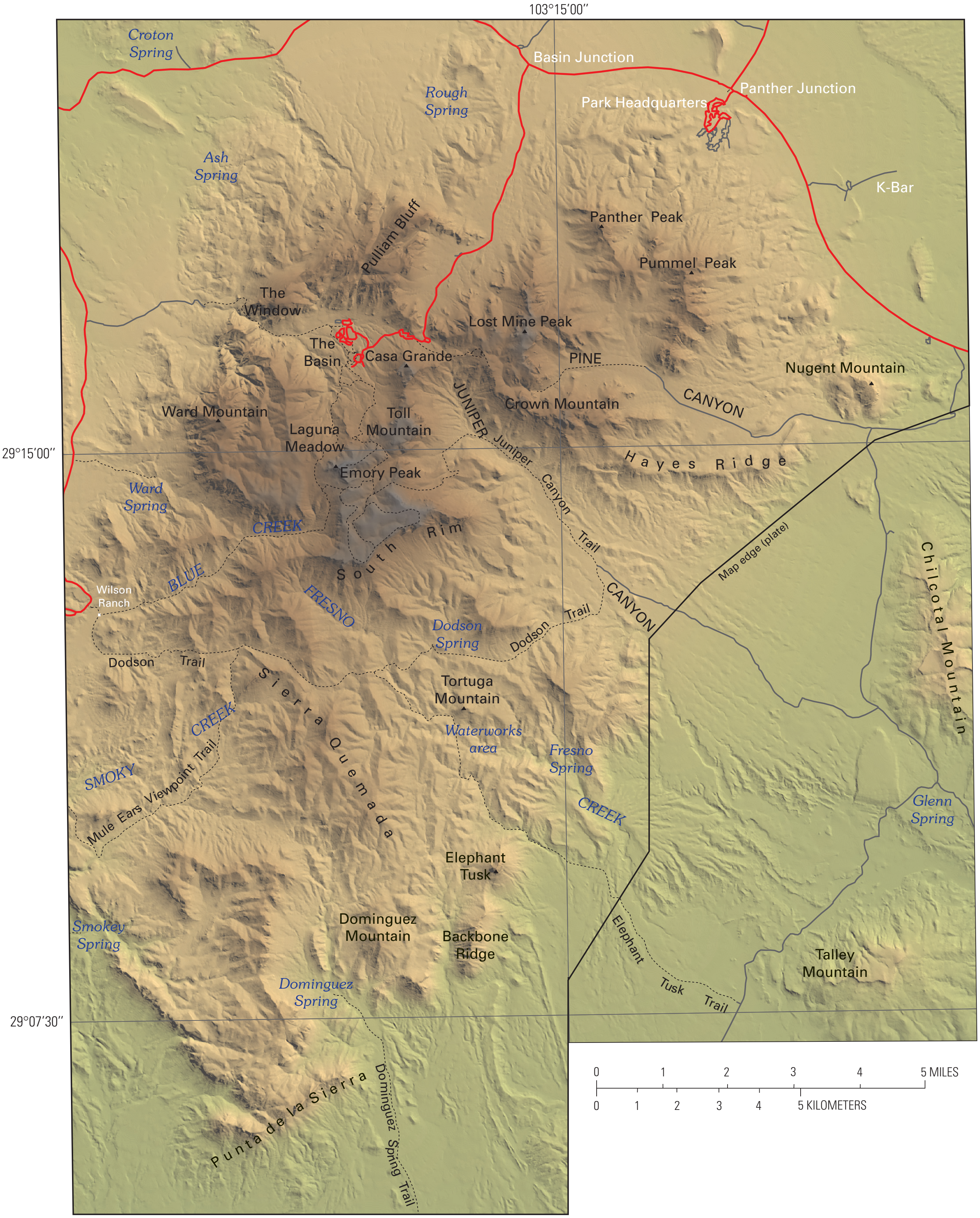


Figure 3. Generalized map of the Chisos Mountains. Topography is color-graded from lowlands in pale green to highlands in dark brown. Paved highways are shown in red, well-traveled gravel and dirt roads in gray, and trails in black dotted lines.

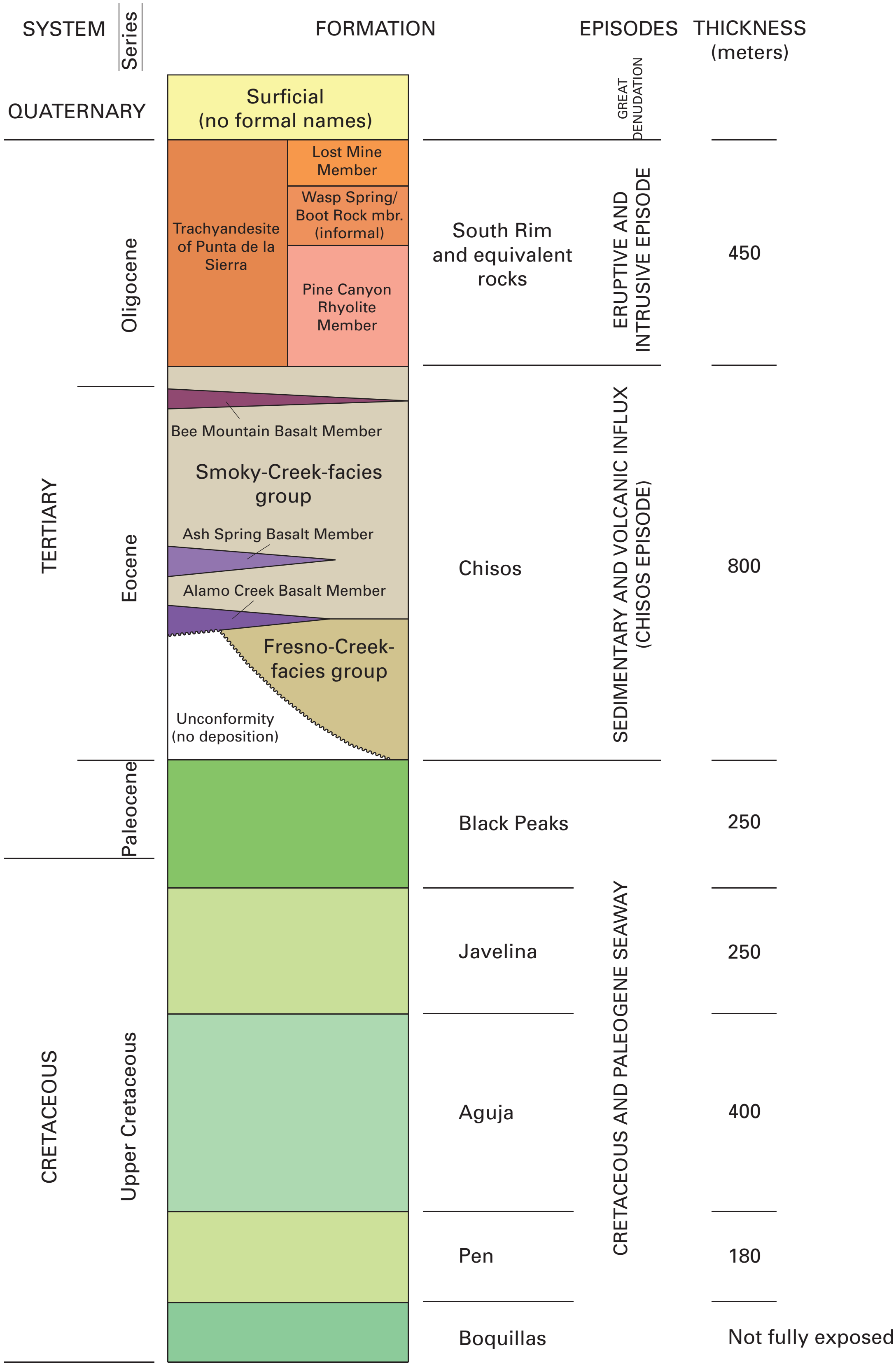


Figure 4. A simple stratigraphic column for the Chisos Mountains. Stratigraphic names shown for Cretaceous and Paleocene rocks are widely accepted. The Chisos Formation as shown is restricted to tuffaceous rocks and intercalated lava flows beneath the ignimbrites of the South Rim Formation, a convention not followed by all workers. South Rim Formation units as shown are not universally agreed upon, but they correspond to those shown on the geologic map (see plate).

debris into the seaway during Pen time. Fossil ammonites and pelecypods attest to marine conditions prevailing over most of this period (Maxwell and others, 1967).

An influx of silt and sand overwhelmed the region, and the remains of the resultant deposits of the Aguja Formation (Kag) are now exposed in the anticline near Cow Heaven Mountain, along the main highway northwest of the Chisos Mountains, and at several locations in The Basin. Marine fossils are present in the oldest of the sand beds, but dinosaur bones, turtle remains, and fossil wood in the younger beds show that the unit became nonmarine with time (Maxwell and others, 1967). Thus, it appears to have evolved from a delta into a river flood plain as marine waters regressed from the area. This unit is evidence that the seaway simply filled slowly with clastic material that eventually displaced the seawater.

The Chisos Mountains region probably remained above sea level to the present day once the Cretaceous seaway waters finally receded. Deposits of claystone with minor amounts of sandstone of the Javelina Formation (Kj) cover the delta and flood-plain sands in a thick sheet. Although not actually preserved in the Chisos Mountains, these beds are known from many other places in Big Bend. Volcanic ash from volcanoes far away provided most of the material that made up the clay that accumulated in widespread mudflats. The sand probably originated in the channels of small rivers that coursed over the mudflats. Dinosaurs wandered the forests that covered these flats (Maxwell and others, 1967).

River sand and tuffaceous clay of the Black Peaks Formation (TKbp) are present in small outcrops to the northeast and northwest of the Chisos Mountains and probably once covered the entire area as well. Fossils of various types of mammals are described from the river floodplain deposits of this unit (Maxwell and others, 1967).

Laramide Orogeny

The slow subsidence and relatively continuous deposition in the marine seaway was interrupted at some time in the late Paleocene or early Eocene by the events of folding and uplift associated with the Laramide compressional tectonism. Strata of early Eocene to middle Eocene age, the Hannold Hill and Canoe Formations have been described elsewhere in Big Bend as Laramide-related deposits (Lehman, 1991). Neither of these units is preserved in the Chisos region. The Laramide deformation has been described as being Late Cretaceous to middle Eocene in age in parts of Trans-Pecos Texas (Muehlberger and Dickerson, 1989; Lehman, 1991), but the nearly continuous subsidence and seaway deposition suggests that it did not affect the Big Bend area until late in this time period. The end of Canoe Formation deposition has been reported to coincide with the end of the Laramide orogeny, locally at about 50 Ma (Lehman and Busby, 2007).

One Laramide fold, a large anticline, occurs on the geologic map between Elephant Tusk and Cow Heaven Mountain and there is a similar one at Mariscal Mountain just south of the map. The folding began in the Late Cretaceous (Lehman, 1991) and was almost over by the time large sills were intruded at about 47 Ma (Harlan and others, 1995). The folds in Big Bend all have long axes that are oriented north-northwest. The folds created a landscape dominated by low northwest-oriented ridges and valleys and this landscape still existed when the first volcanic rocks erupted in the region.

Chisos Episode—Volcanic and Sedimentary Influx

Volcanism was widespread in the southwestern United States and northwestern Mexico, and the stippled pattern on figure 1 shows how extensive it was. Big Bend lies within a large volcanic field known as the Trans-Pecos volcanic belt (Henry and others, 1991). The Trans-Pecos belt is the easternmost of several large contemporaneous volcanic fields that include the Mogollon Datil field, the Sierra Madre-Occidental fields of Sonora and Chihuahua, and numerous others scattered throughout the Sonoran section of the Basin-and-Range (fig. 1). It has been widely acknowledged by volcanologists for a number of years that all this volcanism is unusual for two reasons: it is abnormally widespread and much of it occurred far inland of the active continental edge at the Pacific Ocean. By comparison the Andean arc is only half as wide as the volcanic fields of Mexico and the southwest United States and the most inland of the volcanoes in South America are less than half as far from the Pacific as the Trans-Pecos fields are today. Possibly not all of the volcanism was arc-related. Henry and others (1991) speculated that post-31 Ma volcanism resulted from intraplate extension as opposed to continental-arc volcanism, which dominated prior to then. The big problem with an extensional origin of volcanism in the Chisos Mountains is the tiny volume of post-31 Ma volcanic material (Dan Miggins and others, 2008) and the lack of evidence for any pre-Miocene extension (Dickerson and Muehlberger, 1994). Thus, the volcanism is probably arc-related but its present distribution is probably influenced by the later extension.

The aforementioned mafic sills and the oldest mafic lava flows in the area indicate that volcanism had begun in Big Bend by 46–47 million years ago (Dan Miggins, USGS and others, 2008). Voluminous tuffs and tuffaceous sedimentary rocks of the Chisos Formation indicate significant regional siliceous volcanic activity during the Eocene, but local sources for the volcanic material have not been identified. The Chisos episode is clearly part of the first wave of volcanism in Trans-Pecos Texas.

The volcanogenic sandstone and tuff of the Chisos Formation have for a long time been thought of as being fairly uniform and nondescript in character. Figure 5, which is a diagrammatic representation of the Chisos facies mapped in this report, suggests that this is far from true. Two groups of facies are evident on the geologic map and on figure 5. The older and more regionally restricted group comprises all those

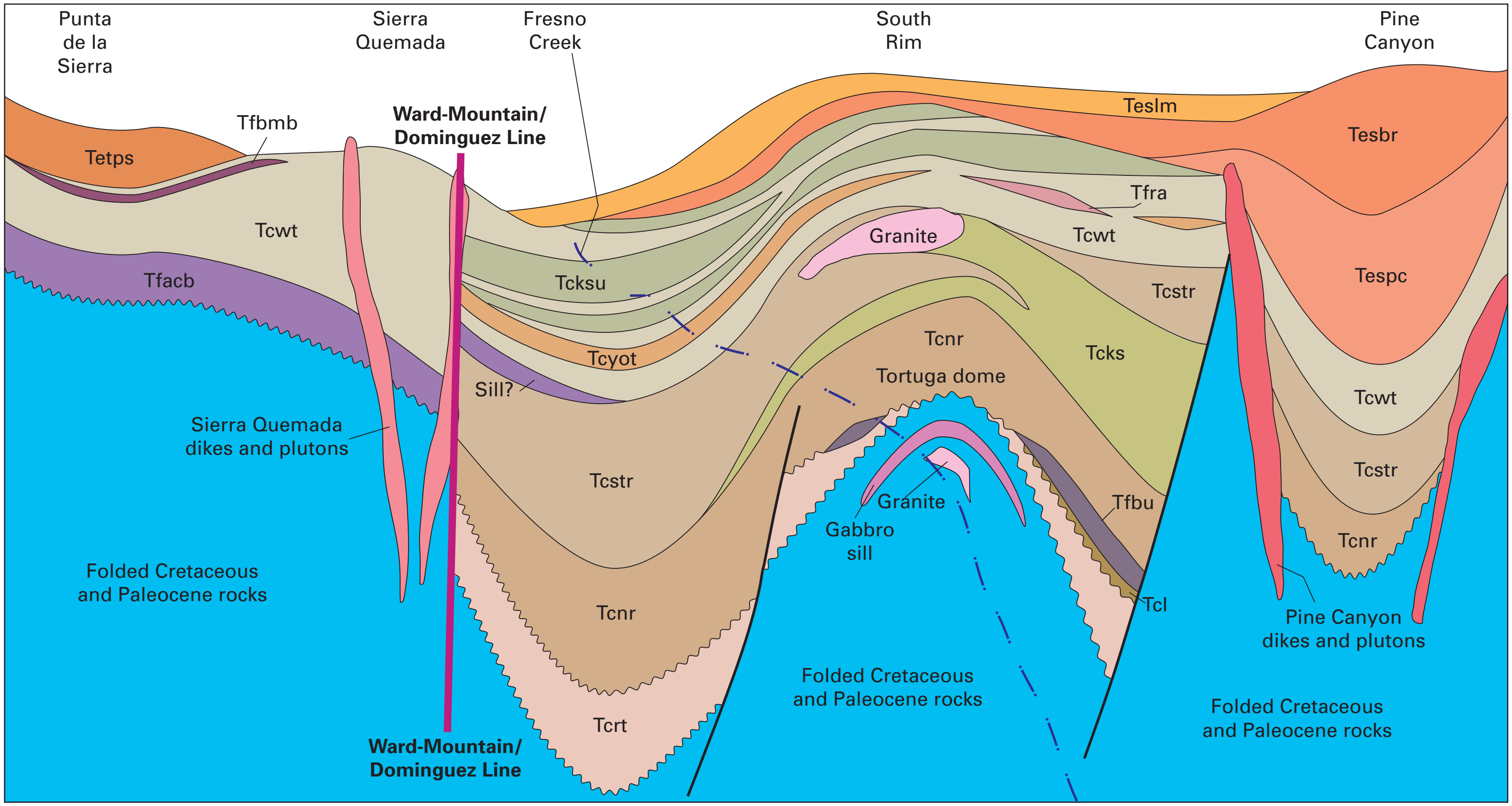


Figure 5. Complex facies relations within the Chisos Formation and eruptive-phase rocks. This diagrammatic view is meant to convey lateral and vertical relationships only and it does not represent a rigorously constructed cross-section line through any one particular area. There is also a considerable, but unconstrained, vertical exaggeration. Unit designations are from the geologic map as: Tcrt, rhyolite and tuff facies; Tcnr, nodular rhyolite facies; Tcl, lacustrine facies; Tcks, siltstone facies; Tcstr, sandstone, tuff, and rhyolite facies; Tfacb, Alamo Creek Basalt Member; Tcwt, white tuff facies; Tcyot, yellow-orange tuff facies; Tfra, rhyolite ash-flow facies; Tcksu, upper siltstone facies; Tfbmb, Bee Mountain Basalt Member; Tetps, trachyte of Punta de la Sierra; Tsbu, basaltic sill; Teslm, Lost Mine Member of South Rim Formation. The fill and outflow from Pine Canyon are listed as Tesbr, lower fill and outflow (Boot Rock member); and Tespc, upper fill and outflow (Pine Canyon Member).

facies beneath the white tuff facies (Tcwt) and the Alamo Creek Basalt Member of the Chisos Formation (Tfacb). This group, which was called the eastern facies by Maxwell and others (1967), only occurs in the Fresno Creek drainage and the eastern Pine Mountain area and it is called the Fresno Creek group in this report. The younger and more widespread group, which was called the western facies by Maxwell and others (1967), is known from many other parts of Big Bend in addition to the Chisos Mountains and it is also present in the northeastern part of the range. It is the thickest and best exposed in the vicinity of Smoky Creek west of Sierra Quemada and it called Smoky Creek group in this report. The map distribution of these two groups is shown on figure 6.

Fresno Creek-Facies Group

Two members of the Fresno Creek-facies group (Tcrt, and Tcl on fig. 5) are restricted to a band of exposure that extends from the flanks of the dome at Tortuga Mountain to the northeast flank of Dominguez Mountain and they are not known from anywhere else, so they are referred to as the localized part of the Fresno Creek-facies group (fig. 6). Their age is poorly constrained at best. They unconformably overlie folded Cretaceous units, but they too are folded by almost as much as the older rocks, so they must predate some of the folding and are probably a little older than 47 Ma. They underlie a sequence of lava flows (Tfbu), but those flows are highly altered and remain undated. These facies may be equivalent in age to the aforementioned Canoe Formation that was deposited elsewhere in the Park during the latter stages of Laramide folding (Lehman, 1991), but no positive correlation has been established.

Rhyolitic tuff and 50 m of very well bedded tuff and mudstone comprise the two localized facies. The rhyolitic tuff indicates there was active volcanism during the early stages of Chisos deposition, but the source of this tuff is not known. Slight angular unconformities are present within and above this section indicating that deformation was occurring while these rocks were being deposited. The unconformities result in thinning of each facies in proximity to Tortuga dome (see fig. 5). The dome, which is cored by thermally metamorphosed Cretaceous rocks, appears to have been a small, but growing topographic high at the time the older Chisos facies were laid down and it acted as a barrier that restricted the distribution of tuffs and flows. The map relations suggest that the two localized facies accumulated discontinuously in low areas associated with folds in the underlying Cretaceous strata, probably as fine unconsolidated air-fall tuff washed into the low areas from the surrounding countryside. The fine-bedded tuff may have accumulated in a small lake or closed depression that formed near the rising dome.

The more widespread members of the Fresno Creek-facies group (Tcnr, Tcstr, and Tcks) are known from the Fresno Creek, Pine Canyon, and northwestern Ward Mountain areas, but nowhere else (figs. 5 and 6). They surround the periphery of the Chisos Mountains, but they do not occur within the high parts of the range. Northeast of Pine Canyon these beds exhibit radial dips inward toward the center of the high mountain mass. Near Fresno Creek they once completely covered the Tortuga dome, but they exhibit slight arching coincident with the old dome, showing that folding was not quite finished as these units accumulated. The pronounced thinning in proximity to the dome, evident in the two localized facies, is not conspicuous in these overlying units however. Thus active Laramide-fold growth must have been greatly diminished, but not over, by the time they were deposited. The radial inward dips around Pine Canyon caldera are also present in younger rock units, so they are assumed to be caused by post-Laramide sagging associated with caldera collapse.

Various rhyolite flows, ash falls, and volcanogenic sandstone beds comprise the widespread members of the Fresno Creek-facies group throughout the Fresno Creek drainage, and surrounding the north and east sides of the Pine Canyon region. West of Juniper Canyon thick local mudstone beds are also present. Mostly these lithologies reflect a volcanic origin, but not the mudstone. Cretaceous mudstone is widespread southeast of Juniper Canyon, and it probably provided the source for similar beds in the Chisos. Some of the Chisos mudstone is thermally hardened, making it easy to distinguish from its source rock, but where unaltered it is nearly identical. The mudstone facies is in fault contact with its Cretaceous source, offering a likely cause for the uplift and erosion of the source area. Much of the rhyolite most likely originated as air-fall tuff or possibly ash flows, but it is extensively recrystallized, making it hard to determine the nature of the original deposit. As it accumulated, it was instrumental in filling in and smoothing out the remnants of topography left over from the earlier folding events.

The Fresno Creek-facies group extends no farther west than Dominguez Mountain or eastern Sierra Quemada (fig. 6). It clearly locally underlies a basalt sill and the facies of the Smoky Creek-facies group in the Fresno Creek area, and it is beneath the Smoky Creek-facies group everywhere east of there (fig. 7 and geologic map, plate). West of Dominguez Mountain, the Smoky Creek-facies group and the Alamo Creek Basalt Member (Tfacb) rest unconformably on Cretaceous beds at Punta de la Sierra. Thus, the entire Fresno Creek-facies group is obviously missing at Punta de la Sierra, due either to erosion or non-deposition (see figs. 5 and 6). Younger intrusive rocks and sediments obscure any details regarding this poorly resolved transition, but it is apparent everywhere to the west of a crude north-south line that extends from southern Ward Mountain to the west side of Dominguez Mountain (fig. 6); referred to as the Ward/Dominguez line.

Smoky Creek-Facies Group

The Ward/Dominguez line also delineates important differences in the Smoky Creek-facies group. West of the line the Smoky Creek-facies group is thick, and it includes several important lava flows, but east of the line it is thin and the lava flows are either not present or very thin and discontinuous.

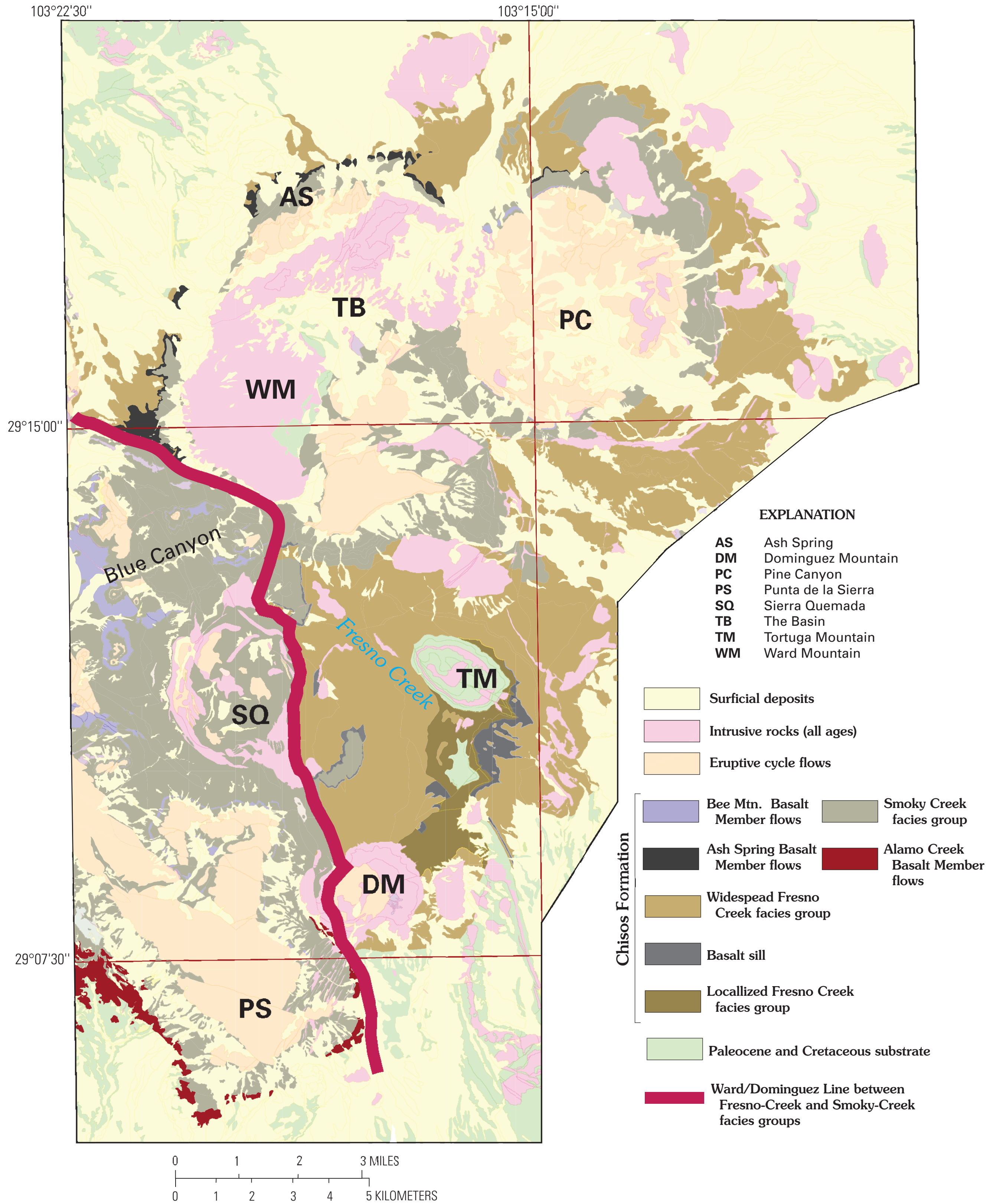


Figure 6. Simplified geologic map of the Chisos Mountains that shows the distribution of the Fresno Creek-facies group of the Chisos Formation (divided into localized and widespread components) relative to the Smoky Creek-facies group. (Note that the Smoky Creek-facies group extends well beyond the Chisos Mountains in the southwest direction).

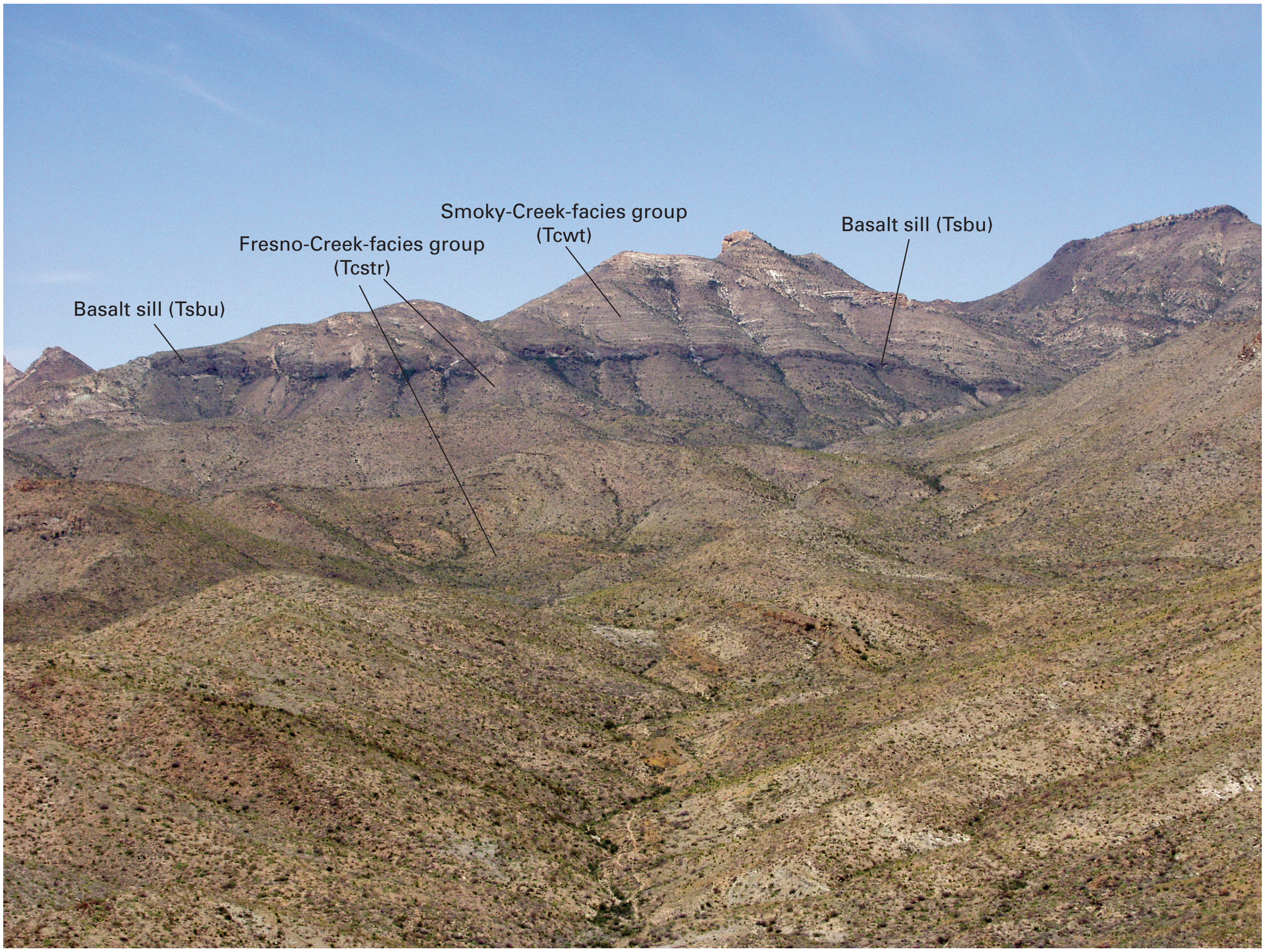


Figure 7. Photograph to the northwest from Fresno Creek showing the Fresno Creek-facies group underlying a basalt sill (Tsbu) that has been dated at about 30 Ma (level dark band of rock crossing mountain front in background) that may have originated in the Dominguez volcano. The sill is overlain by white tuffs of the Fresno Creek-facies group (Tcwt) and underlain by brown-colored sandstone, tuff, and rhyolite (Tcstr) of the Fresno Creek-facies group.

These differences were apparent to Maxwell and others (1967) who attributed them to the influence of a buried anticline in the Cretaceous rocks that they thought extended from The Basin area south to Dominguez Mountain. The evidence for or against an anticline is slim (pl.), but the major stratigraphic differences in the Chisos are real. In addition, numerous faults, the west edge of Dominguez Mountain, the east edge of Sierra Quemada, and the east edge of the Ward Mountain pluton, all lie along this same line (fig. 6). However poorly understood, it is doubtless an important feature.

White tuffaceous sandstone (Tcwt) makes up most of the Chisos Formation southwest of the Ward/Dominguez line. This facies is also present east of the line, where it is much thinner and it interfingers in a complex way with mudstone and brown sandstone (fig. 5). The white tuffaceous sandstone is highly visible from many roads, especially the road to Castalon, so it is the facies that is most commonly thought of as being synonymous with the Chisos Formation. A distinct marker horizon of yellow-orange tuff (Tcyot) is interbedded with the upper part of the white tuffaceous sandstone facies. This tuff sequence is well exposed in Blue Creek Canyon along the Blue Canyon trail. It forms a more-or-less continuous band of outcrop to the east of there to an eventual pinch-out beneath the eastern South Rim (pl.). It is also exposed in the northeast wall of Juniper Canyon and in a small outcrop north of Pine Canyon. The tuffs show that volcanic activity was ongoing somewhere nearby, but the source of the volcanic material is not known. Much of the material may have come from centers outside of the mapped area, although even that is not clear. More work is needed in order to unambiguously define source areas.

The Bee Mountain Basalt Member (Tfbmb) occurs in the upper part of the Chisos Formation, but it is not present everywhere the upper Chisos is found. It is also highly variable in thickness. The thickest and best-exposed Bee Mountain Basalt Member in the Chisos Mountains occurs in Blue Creek Canyon area (fig. 6) and it gets thinner southward to where it locally pinches out near Punta de la Sierra. Similar basalt flows are present in the high Chisos Mountains, but these are thin and discontinuously present. In some places, notably the Juniper Canyon area, two thin flows occur that are separated by tuffaceous beds.

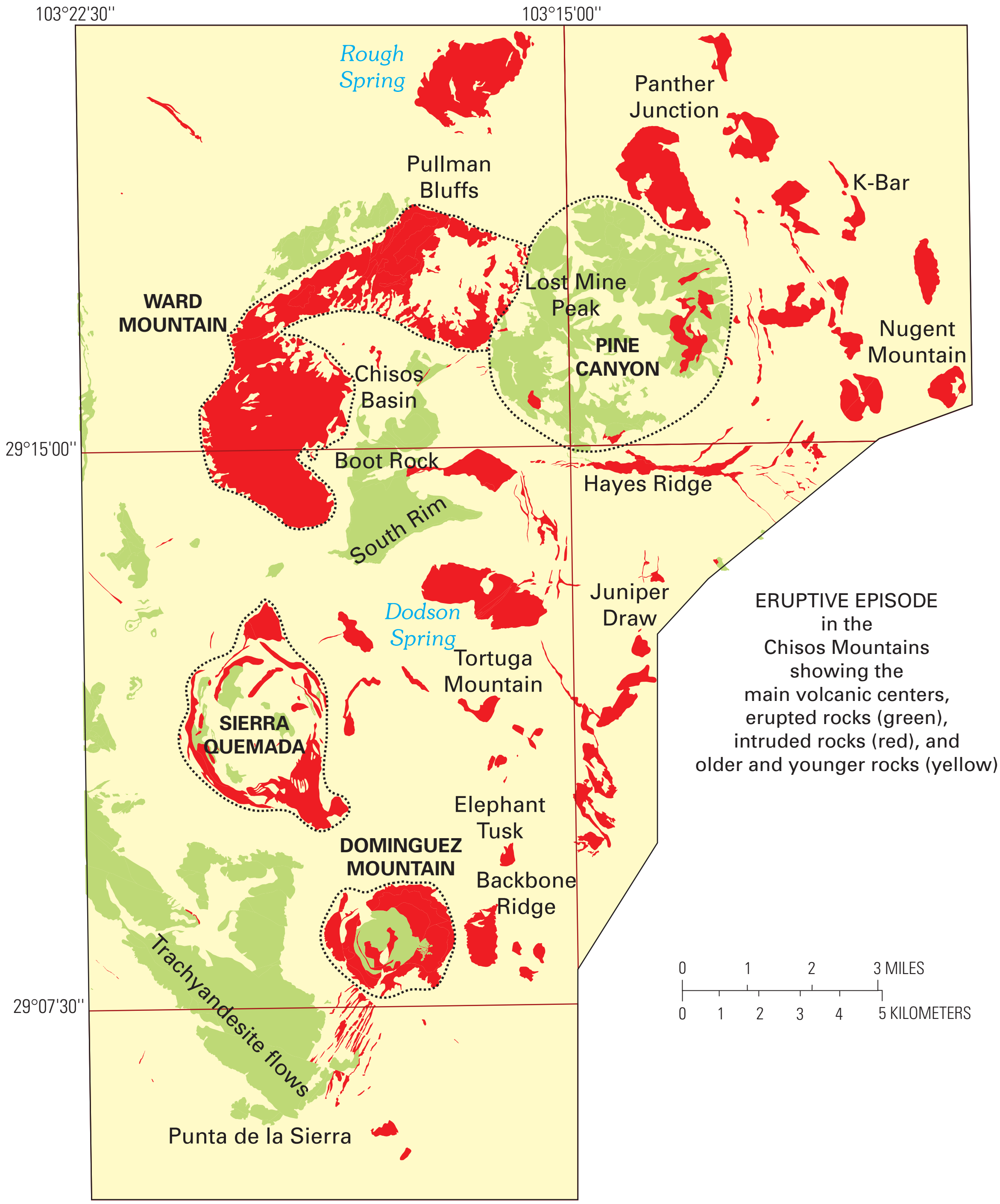


Figure 8. Simplified map showing the distribution of the rocks of the eruptive episode. Dotted lines outline some of the larger intrusive and eruptive centers.

Eruptive and Intrusive Episodes

Calderas, failed calderas, and volcanoes have been described in the Pine Canyon area, at Sierra Quemada, and at Dominguez Mountain, respectively (fig. 8). Numerous eruptions resulted in widespread lava flow and ash flow sheets, particularly at South Rim and Punta de la Sierra. The violent ejection of magma from deep beneath Pine Canyon caused the collapse of a near-circular caldera, which filled with a thick sequence of hot pyroclastic debris (Barker and others, 1986). Large intrusive bodies, such as the one at Ward Mountain, and many smaller ones formed then. Some wide dikes outline the remnants of a failed caldera at Sierra Quemada where a complex ring of wide dikes (Tdsq) is preserved (Scott and others, 2007). A thick sequence of lava flows of trachyte accumulated at Punta de la Sierra. A small volcano, defined by flows, dikes, and ring-shaped intrusions, at Dominguez Mountain may have been the source of the trachyte flows, but this has yet to be demonstrated. All of these features and more are shown on figure 8.

The largest eruptive center was in the Pine Canyon area where a nearly circular collapsed caldera 6–7 km in diameter formed as a result of an explosive eruption from a deep magma source (fig. 8). The outflow and caldera fill associated with this eruption are collectively referred to as the South Rim Formation in this report. The collapsed area in the core of the caldera is revealed by the 10°–40° inward dips of Chisos beds surrounding the feature and by the thick local accumulation of ignimbrites overlying the Chisos. Collapse apparently occurred by sagging of the Chisos in the core area, not by faulting, since faults are not in evidence (Barker and others, 1986). The bowl-shaped sag is evidence for the evacuation of a considerable amount of magma from beneath the core area during several violent eruptions. The collapsed center filled with its own eruptive debris, so the net result of much of the activity was a simple transfer of most of the deep magma to the surface where it filled its own collapse depression. The caldera fill is of two different types. The oldest fill is rhyolitic ash-flow tuff that is at least 300 m thick in Pine Canyon proper and it is mapped as a member of the South Rim, the Pine Canyon Rhyolite Member (Tespc), in this report. The youngest is a thick sequence of flow breccia with a densely welded ignimbrite matrix that is well exposed in the Lost Mine Peak area and is mapped as the informal Boot Rock member (Tesbr) in this report.

Some outflow, primarily from the younger eruptive episodes, managed to escape the caldera confines to flow southwest to the South Rim area. Outflow from Pine Canyon caldera covered the upper Chisos Formation with a thin deposit of non-welded ash flow, tuff, and breccia at least as far to the southwest as the modern edge of South Rim. The latter flows are included in the Boot Rock member (Tesbr)in this report. Eruptions continued after the caldera had completely filled and these resulted in a thick ash-flow sequence, mostly of quartz trachyte, that now covers most of the South Rim plateau. The trachyte, which is referred to as another member of the South Rim Formation, the Lost Mine Member (Teslm), in this report, forms welded-and-nonwelded ash-flow tuffs and local lava flows that overlie the early outflows. The tuffs and flows are mostly unstratified and they resist erosion, forming the steep cliffs that define modern edge of South Rim.

A small volcanic center at Sierra Quemada (fig. 8) began to develop much the same way Pine Canyon probably did, but there is no evidence that it ever exploded, collapsed, and filled (Scott and others, 2007). All that remains of the crudely oblong center is a collection of dikes, stocks, and flows intruding the Chisos. The older Chisos beds that now occupy the interior of Sierra Quemada would have been blown away had this center suffered a major explosive, caldera-forming eruption accompanied by a rapid evacuation of magma. Here there is no pool of young erupted flows in the volcanic center like at Pine Canyon, prompting Scott and others (2007) to describe Sierra Quemada as a failed caldera. Since there is no evidence of a large-scale eruption at Sierra Quemada it is not considered to be the source of any of the large flows in the region.

A small volcano formed at Dominguez Mountain (fig. 9) and numerous vertical dikes radiate into the country rock to its southwest. Dominguez Mountain still preserves the original cone shape of this volcano. The volcano at Dominguez Mountain has not been studied in any detail, but good descriptions exist for the rocks that make it up (Maxwell and others, 1967). Small granitic intrusive bodies surround the Dominguez volcano, and its interior is a mix of layered rocks and dense dike swarms (fig. 9). The layers dip gently outward from the volcanic center and the dikes cut them vertically. The layered rocks in the volcanic core have not been studied. They might be related one of the Chisos facies (for example, Maxwell and others, 1967), but they are much darker gray in color than any of the known Chisos facies and field examination of float at the mountain base did not reveal any Chisos-like samples. Most likely the layered rocks originated as lava flows forming the flanks of the volcanic buildup. The dike swarms (Tdds) form large bodies of rock in which dikes intrude other dikes to the extent that country rock is nearly absent. The dikes include both mafic and intermediate rock types, with intermediate types being more prevalent. Most dikes radiate outward from the volcanic center. Several intrude the east half of the volcano and a small number of dark-colored dikes extend into the country rock to the north. The most conspicuous dikes intrude all the rocks to the southwest of the center and they merge upward into flows of trachyte at the top of Punta de la Sierra (fig. 10).

Trachyte flows (Tetps) form a thick and widespread field of volcanic rock due west of Dominguez Mountain (fig. 8). This field forms high, mountainous ground that extends northwest from Punta de la Sierra to beyond the western edge of the map (pl.). The source of these flows is not known, but their relation to the Dominguez dikes suggests that Dominguez Mountain should be considered as a possibility.

A voluminous intrusive center formed at Ward Mountain and this intrusion now partially encircles The Basin to the north and west. There are also numerous small plutons, stocks,

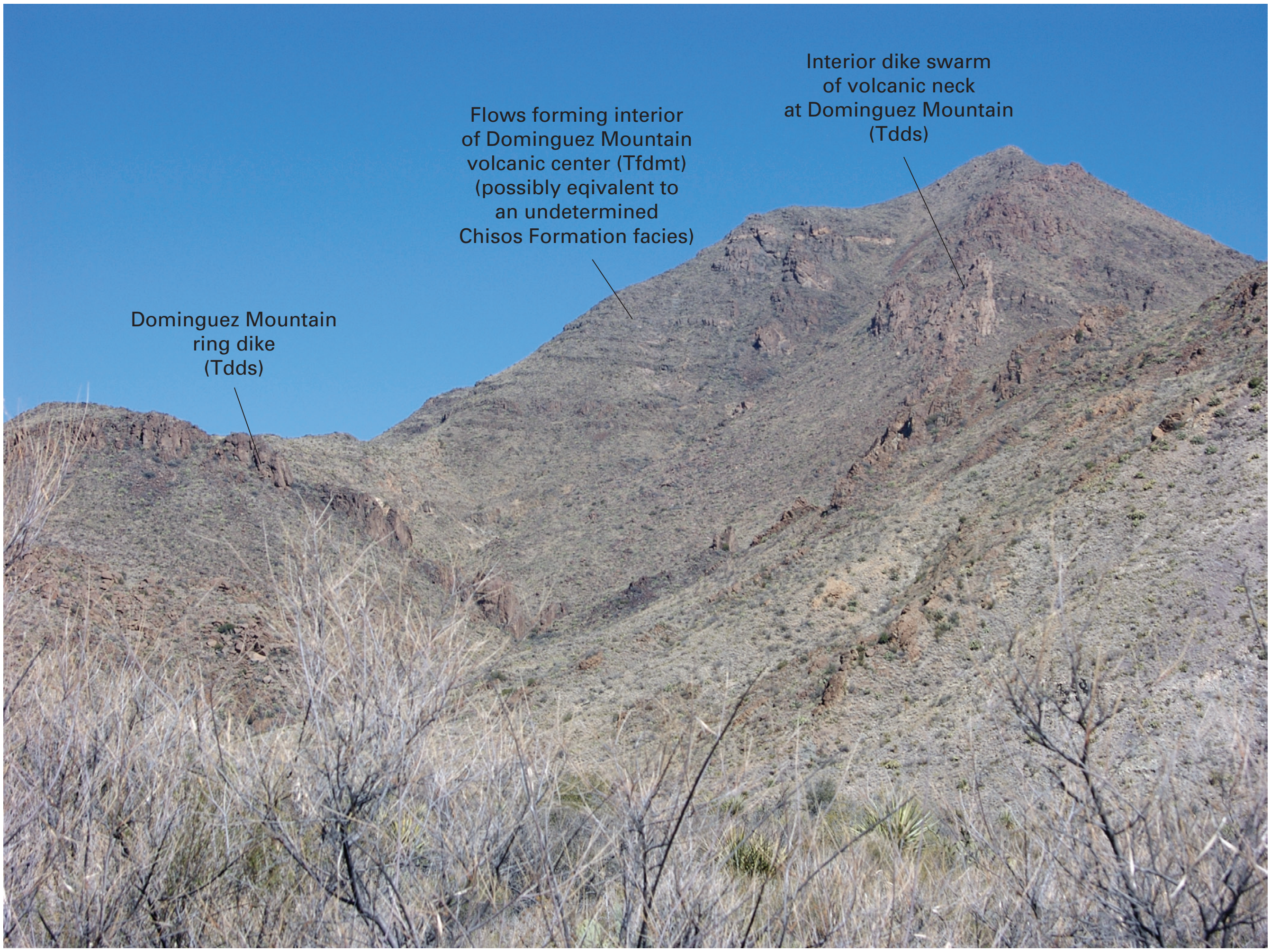


Figure 9. Photograph of Dominguez Mountain taken from the southwest flank.

sills and dikes spread throughout the Chisos Mountains that relate to the various volcanic centers in poorly understood ways. The most prominent of these occur at Backbone Ridge, Elephant Tusk, Tortuga Mountain, Dodson Spring, Rough Spring, Boot Rock, Hayes Ridge, southwest of Panther Junction, in the Nugent Mountain/K-bar area, and near Juniper Draw (fig. 8).

The pluton at Ward Mountain (Tiwm) is a large C-shaped body (fig. 8) that is a complex mix of flow-banded rhyolite and fine-grained granitic rock types. These rocks are very resistant to erosion and they uphold all the steep cliffs and mountainous areas around Ward Mountain west of The Basin and in the Pulliam Bluffs area to the north (fig. 11).

Other small intrusions are scattered from Backbone Ridge in the south to Rough Spring in the north, wrapping around the east side of the range (fig. 8). Small stocks at Backbone Ridge and Elephant Tusk are probably eroded volcanic necks that once were the roots of small volcanoes. Small laccoliths occur at Rough Spring, Dodson Spring, southwest of Juniper Draw, and southwest of Panther Junction (fig. 8). The one at Dodson Spring shows evidence that the injection took place by the intrusion of one dike after another in the eastern half of the body and by one sill after another in the west (fig. 12). The dome at Tortuga Mountain is associated with a thick granodiorite sill and a small intrusion in the core of the dome that may be the top of a buried laccolith. Some of the doming there may be the result of the intrusion uplifting the local country rocks, including the sill. Near Juniper Draw at the east-central border of the map there is also a thick sill of coarse-grained feldspar-rich granitic rock. The numerous small plutons northeast of the range were not examined in any detail.

The eruptive and intrusive episodes took place in the early part of the Oligocene (roughly 29–34 Ma) and new Ar/Ar age data suggest that most of the activity was confined to the 32–32.5 Ma timeframe in the Chisos Mountains (Dan Miggins, USGS, written commun., 2008; and table 1). The new dates from the stratigraphically oldest to the youngest outflows at the base of the South Rim to the top of Emory Peak almost all fall in the 32- to 32.5-Ma range. The largest plutonic body and the older fill of the Pine Canyon caldera fall within this range as well, except one sample from the pluton that might be 0.2 million years older. Outside of the high

Figure 10. Photograph of the southeast point of Punta de la Sierra taken from the southeast. The large near-vertical dikes are part of the complex, southwest-trending swarm of dikes that emanate from the Dominguez Mountain volcanic center. Many of these dikes merge upward into the trachyte flows that form most of the high mass of Punta de la Sierra. Flows and dikes both probably formed during eruptive episodes at Dominguez Mountain. Trachyte flows are about 30 Ma to the south of Punta de la Sierra (Dan Miggins, USGS, written commun., 2005)

Chisos, a small body of explosion breccia (Teeb) from Sierra Quemada dated in the 32.0- to 32.5-Ma range, but another similar sample of it came out at 29.5 Ma. Most of the isolated small plutons are in this range, except Nugent Mountain (31.5 Ma), a dike at Sierra Quemada (29 Ma), and a sill near K-bar that is far out of range at 41 Ma. Trachyte flows in the southern parts of the Chisos Mountains have not been dated, but similar flows near Castalon are between 30.0 and 30.5 million years old.

The precision of the age data is not yet good enough for us to sort out the sequence of events with any degree of confidence within this short time period. Outflow stratigraphy remains our best tool, but that does not help much if we wish to relate plutons to flows or if we want to describe isolated volcanic centers relative to one another. Earlier workers thought the pluton of Ward Mountain (Tiwm) post-dated all the flows in the high Chisos, but at least two ages (32.4 and 32.7 Ma) indicate it may be slightly older than all of them. Sierra Quemada may be the youngest local center if the 29 Ma ages there prove to be accurate (at least one other age from that center falls in the 32.0–32.5 Ma range). Possibly Dominguez Mountain and the trachyte flows in the south formed between the two time periods. More dates are necessary if any of this is to become well established.

Basin-and-Range Extension

The rifting in the Sonoran section of the Basin-and-Range is mostly Miocene in age, beginning about 23 Ma (Dickerson and Muehlberger, 1994), or roughly 5 m.y. after the last major volcanic eruptions in the Big Bend area. There can be no denying the spatial coincidence of extension and volcanism in this part of North America, but any temporal connection is dubious. Extension was probably facilitated by heat from the earlier volcanism rather than being causal to it.

Figure 1 shows that Big Bend National Park is within the eastern extent of the Basin-and-Range near the southern terminus of the Rio Grande rift. Two large grabens in the park form the lower country on either side of the Chisos Mountains. To the northeast is the Estufa bolson, between Panther Junction and Sierra del Carmen, and to the southwest is the Dehlaho bolson between Punta de la Sierra and Sierra Ponce (fig. 2). Both of these grabens filled with sediment during Miocene time. The oldest sediment in Estufa bolson, which is largely

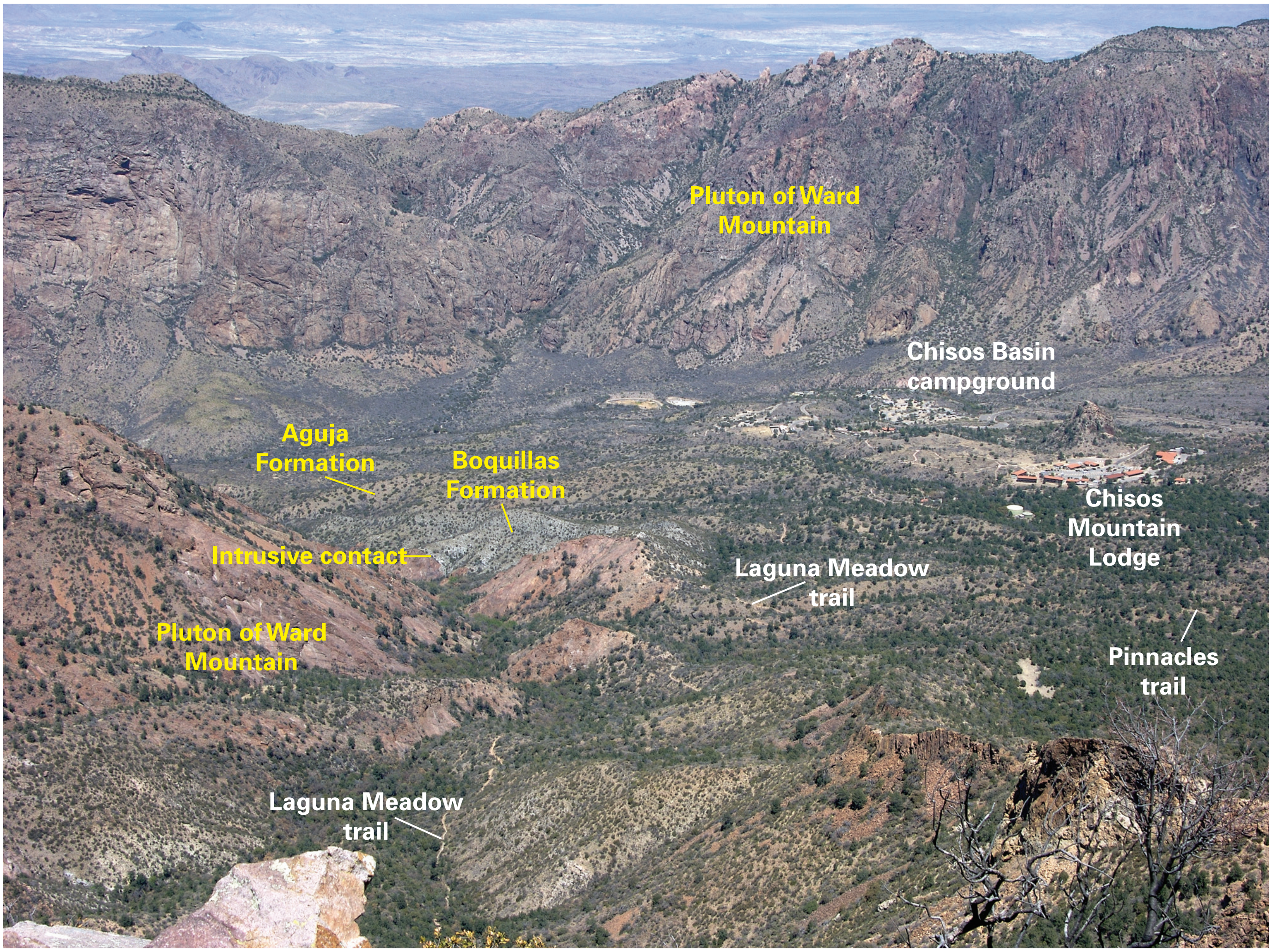


Figure 11. Photograph to the north of The Basin area in the high part of the Chisos Mountains. Several important geologic features are labeled in yellow. Important cultural features are labeled in white. The prominent gap in the mountains, known locally as the window, is to the left (west) of the view as shown.

conglomerate, has been dated at about 10 Ma and the youngest fill is Pliocene (Dickerson and Muehlberger, 1994). Some of the faults that bound the graben apparently were active in the Quaternary and the hot springs near Rio Grande Village are probably related. The Delaho bolson began in the Miocene as early as 23 Ma. Only remnants of the oldest graben fill remain in Big Bend National Park, owing to later erosion related to the incision of the Rio Grande in Quaternary time. The original fill was at least 340 m thick at one time (Dickerson and Muehlberger, 1994).

The Sierra del Carmen, which flanks the Estufa bolson to the east, is a large range consisting of tilted fault blocks primarily formed of Lower Cretaceous limestone that was originally deposited in the Cretaceous seaway. One of the most notable normal-fault escarpments in the area flanks the southwest side of this range near Boquillas del Carmen, Mexico. The amount of extension represented by this faulting is very small compared to other places in the Basin-and-Range, but the range front is topographically impressive.

The southwest edge of Dehlaho bolson occurs at Sierra Ponce, a large southwest tilted block of Lower Cretaceous limestone. The block is tilted gently to the southwest and steep, prominent cliffs mark its northeast edge along the Terlingua fault (fig. 2) upon which 1,000 m of displacement has occurred.

Denudational Episode

It is not clear whether or when Basin-and-Range deformation ended in the park, as some faults show evidence of Quaternary activity and might still be active. However, by the

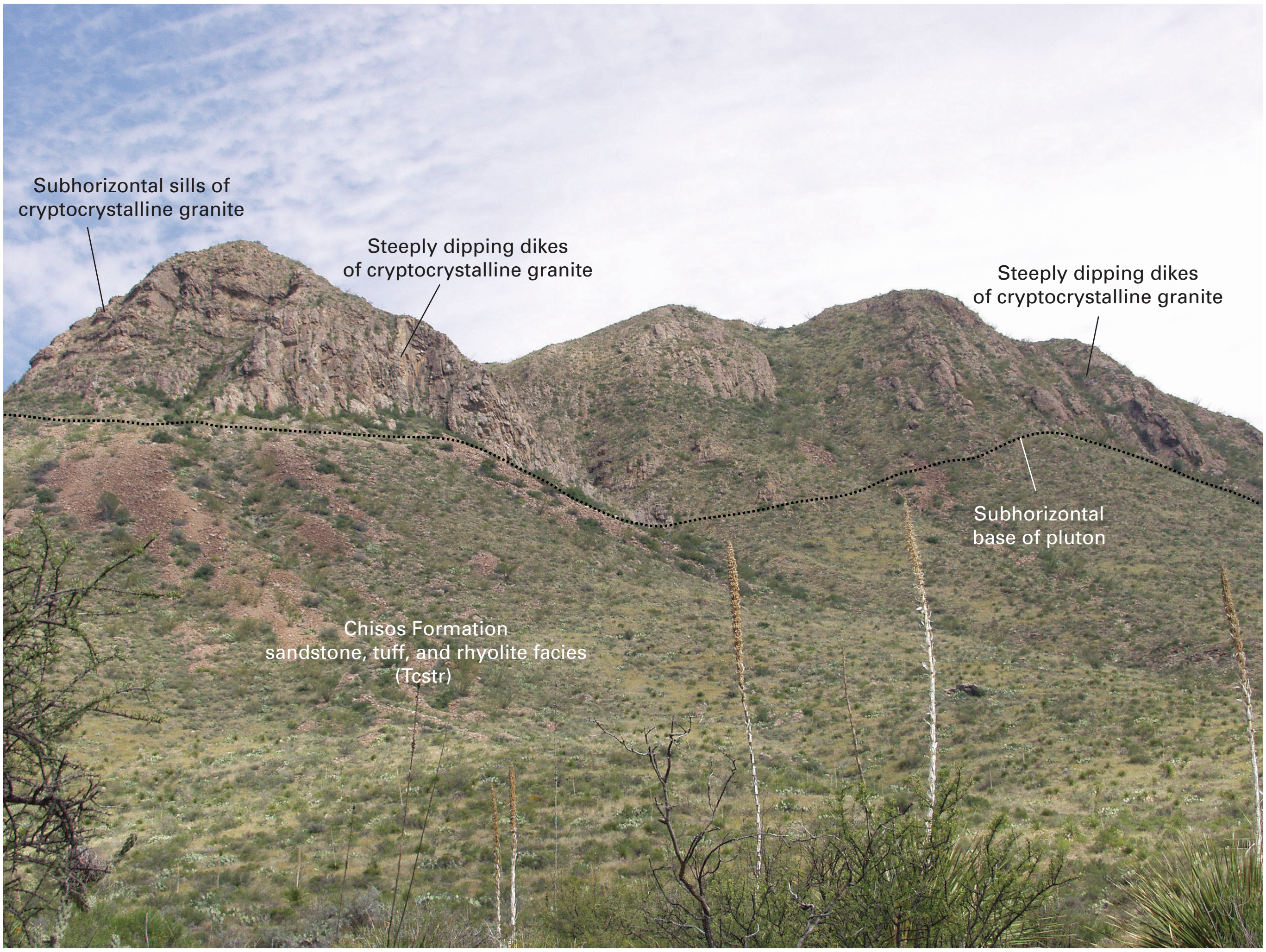


Figure 12. Photograph to the north of a small pluton of cryptocrystalline granite to the east of Dodson Spring. The pluton is formed of dikes that intrude dikes, and sills that intrude sills. The eastern dikes are steep to vertical and the western sills are subhorizontal, parallel to the base of the pluton.

end of the Miocene Epoch about 5 million years ago rates of deformation had slowed and most of the fault activity was over. The grabens were filled with sediment by that time based on the meandering course followed by the Rio Grande even where it cuts the rocky highlands of Sierra Ponce, Mariscal Mountain, and Sierra del Carmen. Regional isostatic uplift and the consequent erosion associated with the incision of the river removed most of the nearly unconsolidated basin fill in fits and starts. Today a complex assemblage of surficial clastic deposits remains as the only record of the denudation. The surficial deposits occur at many different topographic levels and tell a complex story of accumulation and degradation in response to factors like climate changes and irregular stream erosion. These deposits take the form of rock falls, colluvium, wash deposits, alluvial deposits of various ages, landslides, slumps, and debris-avalanches, none of which have been formally named.

One especially notable mass-movement deposit is found on the northwest flank of the mountains just west of Pulliam Bluff. This landslide is big enough to be viewed easily from space (fig. 13), and it is very complex probably having formed in several different events. The rocks within it are almost all fractured to one extent or another, but in the higher parts of the slide large bodies of rock are still intact enough to map as if they were bedrock. Near the downhill end of the slide, the rocks are nearly pulverized and different rock types are mixed up with one another. An attempt was made on the geologic map (pl.) to delineate these areas. Also the primary source rocks are identified in places where the amount of mixing is not too great. The rocks involved in this slide are the Chisos Formation (Alamo Creek Basalt Member (Tfacb) and younger) and several units of the eruptive and intrusive cycle. All these units slid to the northwest over mudstones of Cretaceous age beneath them. The sliding probably occurred

Table 1. Radiometric age determinations of select rocks in the Chisos Mountains.

[Ar/Ar refers to $^{40}Ar/^{39}Ar$ method of isotopic dating and SHRMP refers to senstive high resolution ion microprobe technique for uranium-lead dating of zircon. MapX is Universal Transverse Mercator NAD 27 horizontal position in meters, and MapY is vertical position. Data supplied by Dan Miggins, USGS written commun., 2008.]

Number	Unit	Age (Ma)	Method	Sample	MapX	MapY
1	Terf	32.11 ± 0.11	Ar/Ar	17DM-5-1-03	664884	3236530
2	Tdsrp	32.12 ± 0.10	Ar/Ar	16DM-5-1-03	669644	3236517
3	Tesbr	32.11 ± 0.23	Ar/Ar	32DM-5-4-03	669318	3238420
4	Tesbr	32.23 ± 0.07	Ar/Ar	131DM-2-11-05	668923	3239649
5	Tesbr	32.21 ±0.05	Ar/Ar	132DM-2-11-05	668945	3239603
6	Tesbr	31.93 ± 0.13	Ar/Ar	TPC-407	664672	3235973
7	Tesbr	32.43 ± 0.29	Ar/Ar	TPC-414	664708	3236872
8	Terf	32.03 ± 0.10	Ar/Ar	TPC-315	666268	3238853
9	Teeb	29.5 ± 0.07	Ar/Ar	4BS11.3.05	662742	3230020
10	Tdsq	29	Ar/Ar	2BS22.1.05	662419	3232023
11	Tsbu	31	Ar/Ar	4BS22.1.05	663815	3231737
12	Tetc	32.1 ± 0.3	Ar/Ar	144DM-3-12-05	658849	3233872
13	Tdsrp	41.6 ± 0.4	SHRMP	75DM	677043	3243161
14	Tsf	32.3 ± 0.3	SHRMP	EC43 (G-11)	671934	3231401
15	Kags	81.7 ± 1.0	SHRMP	04LS07	667265	3230394
16	Kags	76.8 ± 0.7	SHRMP	04LS06a	667008	3231129
17	Tcyot	41.4 ± 0.5	SHRMP	6DM	659903	3233103
18	Terf	32.3 ± 0.4	SHRMP	16DM-5-1-03	664713	3236435
19	Tdsrp	32.6 ± 0.6	SHRMP	33DM-5-4-30	675552	3237371
20	Tinm	31.5 ± 0.3	SHRMP	128DM	676885	3237714
21	Tiwm	32.4 ± 0.3	SHRMP	138DM	662955	3239942
22	Tiwm	32.7 ± 0.3	SHRMP	139DM	662388	3240360
23	Teeb	32.3 ± 0.7	SHRMP	3BS	662689	3229967
24	Tfvt	32.1 ± 0.3	Ar/Ar	144DM-3-12-05	658880	3233689
25	Tsgb	26-30	SHRMP	04LS09	668244	3229679
26	Tfasb	40.38-43.39	Ar/Ar	2BS27.203	658352	3236702
27	Tfbmb	33.74 ± 0.12	Ar/Ar	153DM-3-18-05	659168	3231740

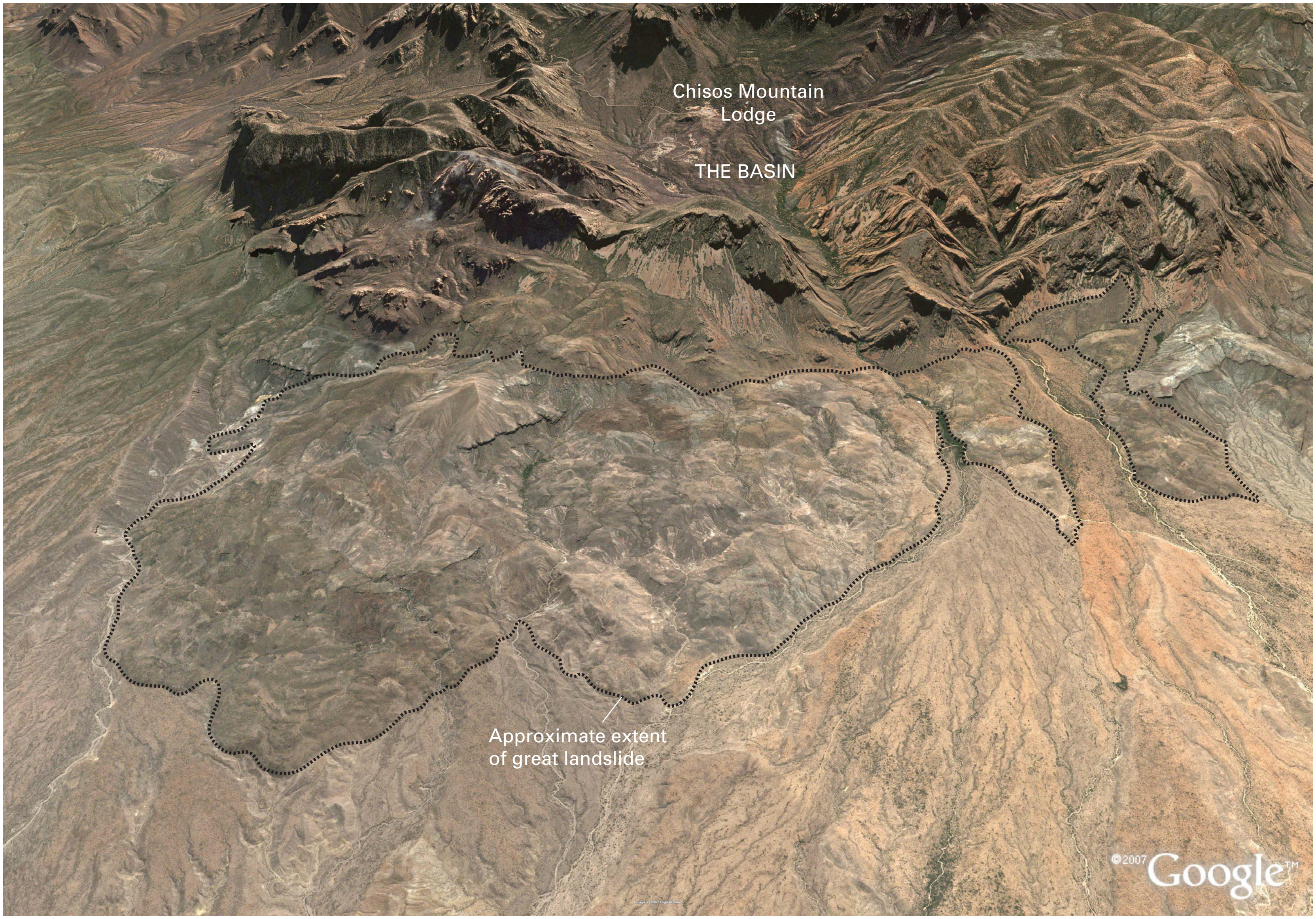


Figure 13. View to the southeast of the large landslide in the vicinity of Ash Spring. This rendition, derived from images in Google Earth™ (see http://earth.google.com/), gives an excellent view of the undulating and lobate land surface that characterizes the slide.

during a prolonged wet period when the underlying mudstone, charged with groundwater, was weakened and gave way under the weight of the overlying rock column.

Description of Map Units

(Map descriptions of bedrock units are summarized from field observations and from descriptions found in various published literature sources. Descriptions of surficial units were provided by Margret Berry (written commun., 2006). Color terms are descriptive of fresh rock surfaces, unless otherwise noted.)

Surficial Deposits

Deposits of the denudational episode. Stages of soil-carbonate morphology follow criteria outlined in Birkeland (1999), modified from Gile and others (1966, 1981) and Machette (1985).

Sedimentary Rocks

Qya **Alluvium, undivided (Holocene to latest Pleistocene)**—Alluvial fan, pediment, and stream deposits. Unconsolidated to weakly consolidated, poorly to moderately well-sorted, poorly to moderately well-bedded gravel, sand, and silt. Cobble- and small boulder-size clasts common. Clasts typically subangular to subrounded, locally angular or well rounded. Bar and swale topography and braided channel morphology commonly well preserved. Typically has low relative height, but buries older alluvial deposits at some mountain front and up-valley locales. Thickness variable from less than 1 m to at least 8 m

Where divisions within Qya are evident and large enough to map separately, unit is subdivided into Qya1 and Qya2 as follows:

Qya1 **Younger alluvium (Holocene)**—On or within several meters of valley floor. Occasionally flooded. Little or no pavement, varnish, or soil-carbonate development

Qya2 **Older alluvium (latest Pleistocene)**—Generally elevated 3 m or more above the valley floor. Surfaces generally planar and partly incised. Pavement weakly developed to densely packed and uniform. Clasts with pavement are lightly to well varnished; varnish colors typically strong brown, yellowish red, dark reddish brown, and black

Qrf **Rock fall deposits (Holocene)**—Generally unsorted, angular, cobble- to boulder-sized rock fragments forming talus on steep slopes. Thickness is 0–3 m

Qc **Colluvium and colluvial fans (Holocene)**—Unconsolidated to moderately consolidated, unsorted to poorly sorted, nonbedded to weakly bedded mixture of gravel, sand, silt, and clay. Locally cemented by carbonate. Cobble- to boulder-size clasts common. Clasts angular to subangular. Forms thin mantle of debris or thicker, fan-shaped colluvial accumulations on flanks of steep slopes. Commonly ribbed or fluted due to various combinations of rainwash, sheetwash, creep, and mass-wasting processes active on steep slopes. Locally includes bedrock outcrops too small to map separately. Thickness variable from about 1 m to over 6 m

Qe **Eolian sand (Holocene)**—Unconsolidated, moderately to well-sorted, silty fine- to medium-grained sand, locally intermixed with small amounts of fine gravel. Very pale brown. Commonly forms small dunes around the base of brushy vegetation. Several small occurrences in northwest part of map north of Chisos Mountain front. Thickness generally less than 1 m

Qs **Spring deposits (Pleistocene)**—Powdery to well-cemented, white, very pale brown, light brownish-gray, or gray, fine-grained, spring-generated calcium carbonate mixed with fine sand and silt; locally nodular or laminated. One small occurrence southeast of Elephant Tusk. Thickness is not known

Qia **Intermediate age alluvial deposits, undivided (late and middle Pleistocene)**—Alluvial fan, pediment, and stream deposits. Locally includes Qya in deposits too narrow or small to map separately. Weakly to moderately well-consolidated, poorly to moderately well-sorted, poorly to moderately well-bedded gravel, sand, and silt. Cobble- and small boulder-size clasts common to abundant. Clasts typically subangular to subrounded, locally rounded. Surfaces generally planar, partly incised and slightly rounded at the edges. Pavement weakly developed to densely packed and uniform. Varnish on pavement clasts ranges from almost none where pavement contains mostly limestone clasts, to moderately varnished with strong brown, yellowish-red, and dark reddish-brown colors. Typically has intermediate relative height, but buries older alluvial deposits at some mountain-front locales. Seismic data indicate that on the north side of the Chisos Mountains, stacked alluvial sequences that include Qia and older alluvium reach total thicknesses in excess of 50 m. Thickness of Qia typically variable from less than 1 m to about 10 m

Where divisions within Qia are evident and large enough to map separately, unit is subdivided into Qia1 and Qia2 as follows:

Qia1 **Younger intermediate age alluvial deposits (late Pleistocene)**—Typically has a stage-I to -II soil-carbonate horizon 1 to 1.5 m thick. Less commonly soil profile includes a 30 to 50 cm thick weakly cemented stage III carbonate horizon. Some surface clasts weathered and (or) split

Qia2 **Older intermediate age alluvial deposits (middle Pleistocene)**—Typically has a weakly to moderately cemented, stage-III to -IV soil-carbonate horizon 1 m or more thick. Weathered and (or) split surface and subsurface clasts common at some locales. Forms higher surface relative to Qia1

Landslide deposits (Pleistocene)—Slumps, flows, and slides of bedrock, colluvium, and alluvium. Terrain typically hummocky or irregular with closed depressions and spires. Thickness is at least 60 m, possibly as great as 100 m. These deposits typically came from single source areas and are subdivided, based on primary lithology that makes them up as follows:

Qlb **Basalt source**—Derived from Alamo Creek Basalt Member of Chisos Formation (Tfacb) south of Punta de la Sierra, and Ash Spring Basalt Member of Chisos Formation (Tfasb) north of The Basin

Qlc **Chisos Formation source**—Mostly derived from white tuffaceous facies of Chisos Formation (Tcwt)

Qlg **Granitic source**—Mostly derived from nearby felsic granite sill (Tsf)

Qlj **Javalina Formation source**—Mostly derived from nearby claystone of Javalina Formation (Kj)

Qlu **Undifferentiated source**—Derived from a variety of source rocks

Qls **Sandstone source**—Mostly sandstone of unknown derivation

Qlt **Trachytic source**—Mostly trachyte derived from trachyte flows of Punta de la Sierra (Tetps)

Qlp **Pine Mountain source**—Mostly derived from Pine Canyon Rhyolite Member of South Rim Formation (Tespc)

Qoa **Old alluvium (middle to early Pleistocene)**—Alluvial fan, pediment, and stream deposits. Locally includes Qya where those units are too narrow or small to map separately. Typically moderately to well-consolidated, poorly to moderately well-sorted, poorly to moderately well-bedded gravel, sand, and silt. Cobble- and small boulder-size clasts common to abundant. Clasts typically subangular to subrounded, locally angular or rounded. Surfaces typically eroded and dissected into broad, rounded ballenas, especially where gravel deposits are thick, but may also be gently undulatory, or form generally planar remnants 30 to 50 m above valley floor. Soils typically have a weakly to moderately cemented carbonate horizon 1 m or more thick. Weathered surface and subsurface clasts common. Pavement ranges from weakly developed to moderately packed and uniform. Varnish on pavement clasts ranges from none where pavement contains mostly limestone clasts, to moderately varnished with yellowish-red and dark reddish-brown colors. Typically has higher relative height than Qia, but is buried by younger alluvial deposits at some mountain front and up-valley locales. Thickness is typically 4 m to 10 m

QTa **Extremely old alluvium (early Pleistocene and Pliocene)**—Moderately to well-consolidated, poorly to moderately well-sorted, poorly to moderately well-bedded gravel, sand, and silt predominantly of alluvial fan origin; exposed along the west map edge and in northeast map corner. Cobble- and boulder-size clasts common. Clasts angular to subrounded. Surfaces eroded and deeply dissected into ballena morphology. Where preserved, soils have carbonate horizon as much as 2 m thick. Total thickness is variable with a maximum of 35 m within mapped area, possibly greater elsewhere

Flows and Intrusions of the Eruptive and Intrusive Episodes (Oligocene)

Tsgb **Gabbro sill**—Gabbro sill intruding metamorphosed Cretaceous rocks in water-works area along Fresno Creek. Described by Lonsdale and Maxwell (1967) as dark gray and medium grained with labradorite crystals as large as 8 mm and augite as large as 4 mm. Texture is seriate and partly ophitic. A poorly resolved U/Pb SHRMP age of 26–30 Ma (table 1) suggests that this may be one of the youngest intrusive bodies in Chisos region. Thickness approximately 15 m

Tebr **Breccia**—Volcaniclastic breccia exposed at tops of several small hills near central-west map border south of Blue Creek Canyon. Overlies tuff and conglomerate unit (Tetc). Thickness approximately 25 m

Terf **Rhyolite flow**—Young rhyolite flows exposed at 1) top of Emory Peak, 2) top of Casa Grande, 3) northwest part of Sierra Quemada, and 4) extreme west map boundary. At Emory Peak and Casa Grande, these flows have been included by most workers with Burro Mesa Rhyolite Member of the South Rim Formation, but new dates indicate that flows at Emory Peak and Casa Grande are too old to be Burro Mesa, which is 29 Ma. At Emory Peak, rhyolite is medium-grained, crystal-rich tuff (fig. 14); rhyolite forms a localized lava dome at Casa Grande. At the west-central map area there is an incomplete section of medium-grained, gray rhyolite ash-flow tuff that is siliceous, highly welded, and has quartz phenochrysts in a rebeckite matrix. This ash flow is not dated in mapped area, but elsewhere numerous ages on it have a consistent average of 29 Ma. It is typically mapped as a member of the South Rim Formation, but is younger and probably had a different source.

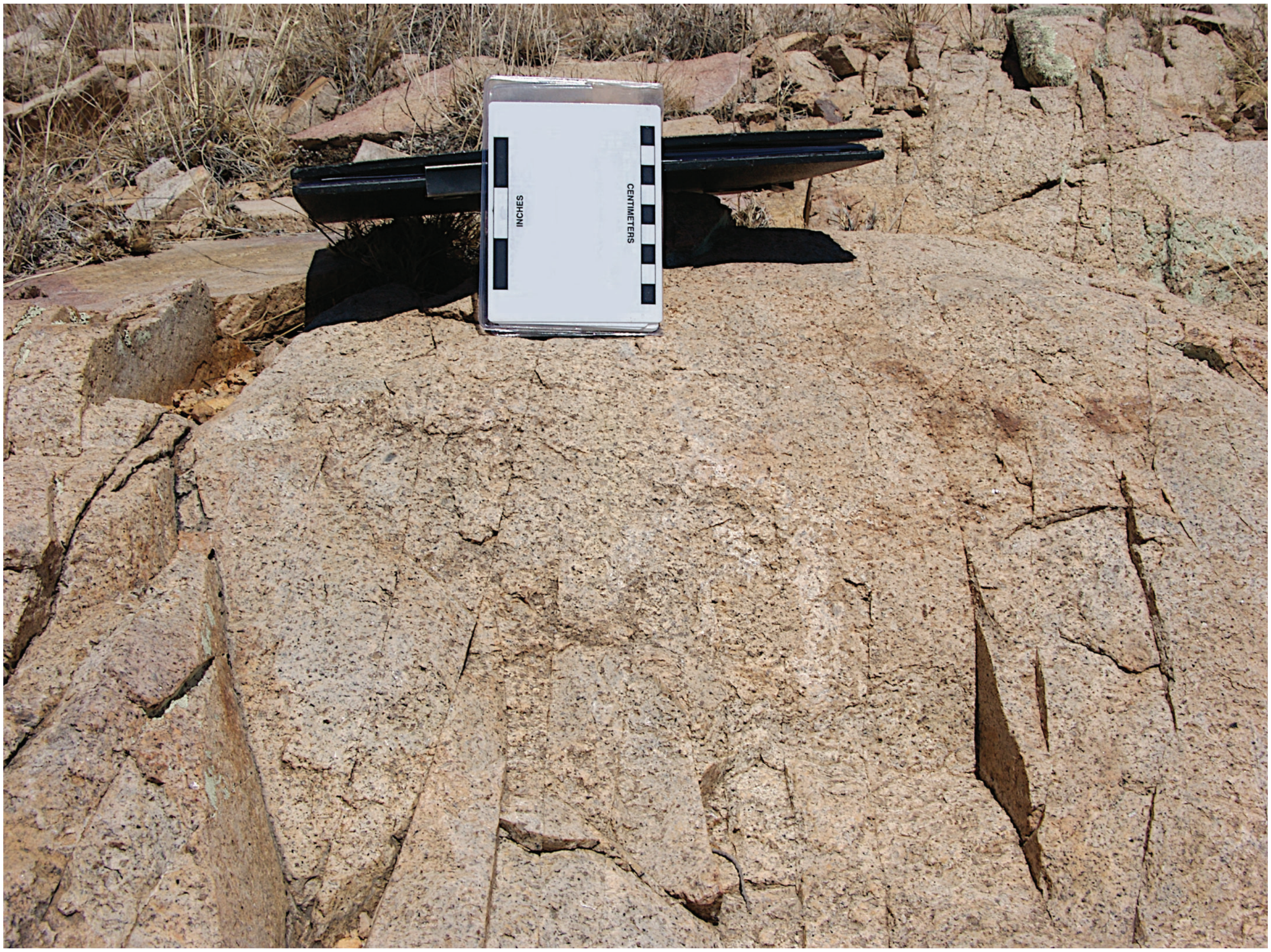


Figure 14. Photograph of crystal-rich tuff that forms the ryhyolite flows near the top of Emory Peak (Terf). White pad shows two scales: 3 in. on the left and 9 cm on the right.

Therefore it is not considered to be part of South Rim. Flows at Sierra Quemada are of local derivation. Thus, these different outcrops are not mapped as Burro Mesa Rhyolite Member herein and they are not included with South Rim Formation, as has been done in the past. Age determinations # 1 = 32.11 ± 0.11 Ma (Ar/Ar), # 8 = 32.03 ± 0.1 Ma (Ar/Ar), and # 18 = 32.3 ± 0.4 Ma (SHRMP) (table 1) on flows at top of Emory Peak and Casa Grande; other locations have not been dated within mapped area. Thickness about 100 m at Emory Peak

Teeb **Explosion Breccia of Sierra Quemada**—Extremely lithic-rich, rhyolitic explosion breccia scattered within perimeter of ring dikes of central Sierra Quemada. Lithic fragments within explosion breccia (mm-size to 200 m long) consist of vertically standing, highly elongate, Tertiary, Cretaceous, and Paleozoic rocks. Age determinations # 9 = 29.5 ± 0.07 Ma (Ar/Ar) and # 23 = 32.3 ± 0.07 Ma (SHRMP) (table 1). Thickness not known

Tetps **Trachyte flows of Punta de la Sierra**—Trachytic flows, resistant, brown, porphyritic trachyte that has a gray to brownish-gray groundmass and feldspar phenocrysts as large as one-half inch across (1–2 cm). The groundmass is darker than phenocrysts, producing a spotted pattern, not unlike that in more mafic dikes at Dominguez Mountain (Maxwell and others, 1967). Phenocrysts include both alkalai feldspar and plagioclase with latter being more common and groundmass includes microphenocrysts of clinopyroxene. Mostly occurs in Punta de la Sierra and in mountainous region to north. Discontinuous exposures also present on northwest flank of Chisos Mountains and in Homer Wilson Ranch area. Source unknown. Thickness about 300 m at Punta de la Sierra. Similar flows nearby to south dated at approximately 30 Ma (Dan Miggins, written commun., 2008). Originally mapped as Tule Mountain Trachyandesite (Maxwell and others, 1967), but that unit is known to be 3 million years older than this sequence of flows

South Rim Formation (Oligocene)

Widely exposed on South Rim and in Pine Canyon Region. Divided into several members as follows:

Teslm **Lost Mine Member**—Description based on Barker and others (1986). Quartz trachyte ash-flow tuffs and local lava flows; densely welded, lacking lithic clasts; contains sparse phenocrysts of subhedral anorthoclase and clinopyroxene. Forms prominent cliffs along South Rim. One K/Ar age determination reported by Barker and others (1986) of 33.3 ± 0.7 Ma. Thickness about 120 m at South Rim

Tesbr **Boot Rock member (informal)**—Description based on Barker and others (1986). Composed of two ash-flow tuff facies, caldera fill, and outflow. Caldera fill is multi-colored breccia with densely welded glassy matrix; contains up to 75 percent by volume of subangular lithic fragments of quartz trachyte and rhyolite. Rhyolite clasts are mostly from underlying Pine Canyon Rhyolite Member of South Rim Formation. Caldera fill is about 100 m thick. Outflow facies is poorly welded or not welded, contains a variety of breccias and ash flows, and is 10 to 20 m thick. Age determinations #4 = 32.23 ± 0.07 Ma, # 5 = 32.21 ± 0.05 Ma, # 6 =31.93 ± 0.13 Ma, and # 7 =32.43 ± 0.29 Ma, (all Ar/Ar) (table 1). Thickness highly variable, about 275 m at Casa Grande

Tespc **Pine Canyon Rhyolite Member**—Description based on Barker and others (1986). Consists of multiple cooling units of peralkaline rhyolitic ash-flow tuff, light brown-gray, densely welded, contains euhedral to subhedral anorthoclase phenocrysts. Rounded fragments of quartz trachyte are abundant in upper part of unit. Eruption led to collapse of Pine Canyon caldera and Pine Canyon Rhyolite Member is mostly confined to collapsed central part of caldera; at least 300-m thick within collapsed area. Age determination # 3 = 32.11 ± 0.23 Ma (Ar/Ar) (table 1). Thickness greater than 580 m in Pine Canyon area

Tesre **Rocks equivalent to South Rim Formation (Oligocene)**—Other rhyolite flows and ignimbrites equivalent to South Rim flows or trachyte flows of Punta de La Sierra (Tetps), but not continuous with any of those units; exposed in Blue Creek Canyon area. Thickness not known

Tiwma **Altered parts of Ward Mountain pluton (Oligocene)**—Altered zone at top of Ward Mountain pluton; not studied

Tii **Intermediate to mafic intrusion (Oligocene)**—Chiefly diorite, possibly gabbro. In several small intrusive bodies south of Tortuga dome in Fresno Creek

Tdsrp **Rhyolite porphyry dikes and sills (Oligocene)**—Various porphyritic dikes and sills, mostly rhyolite or rhyodacite in composition, includes “ring-dike complex” of Pine Canyon caldera; also exposed in numerous localities in eastern part of map. Ring-dike complex at Hayes Ridge (fig. 3) was described as light-gray sodic granophyre with chalky microperthite and a microcrystalline groundmass (Lonsdale and Maxwell, 1967). Age determinations # 2 = 32.12 ± 0.10 Ma (Ar/Ar) and # 13 = 41.6 ± 0.4 Ma (SHRMP) (table 1)

Tdds **Dominguez Mountain dike swarms (Oligocene?)**—Mostly light-colored rhyolite to dacite porphyry, mapped as a discrete unit in Dominguez Mountain area where dike-on-dike intrusion forms a wide body of dike rock. Rhyolite dikes are abundant, particularly southwest of volcanic center where they pass upward into trachyte flows at Punta de la Sierra. These are pale yellow brown and fine grained, most contain sparse white subhedral feldspar phenocrysts, and are slightly vuggy (fig. 15*A*). In rare cases, interior parts of widest dikes are medium to coarse grained. In these cases, feldspar grains are dense enough to be in contact with one another, and matrix is red brown and medium grained.

Figure 15. Photographs of types of dikes in the Dominguez Mountain dike complex (Tdds). (*A*) Rhyolite and (*B*) porphyritic syenodiorite. Pencil for scale.

Rare mafic dikes are also present (fig. 15*B*) and these coarse-grained and porphyritic dikes are probably olivine syenodiorite or syenogabbro according to Maxwell and others (1967). Not dated, but presumably equivalent in age to 30 Ma trachyte flows of Punta de la Sierra

Tdsq **Sierra Quemada dike complex (Oligocene)**—Thick dike-like intrusions that form outer rim of volcanic center. Lonsdale and Maxwell (1967) described them as augite-microgranite porphyry, ganophyre, and porphyritic rhyolite. Age determination # 10 = 29 Ma (Ar/Ar) (table 1)

Tdr **Rhyolite dikes of Sierra Quemada (Oligocene)**—Rhyolite dikes in Sierra Quemada; not dated

Tsf **Felsic sill (Oligocene)**—Gray feldspar-rich, porphyritic riebeckite microgranite with weathered alkalai-feldspar phenocrysts set in a groundmass of weathered laths of alkalai feldspar and anhedral quartz (Lonsdale and Maxwell, 1967) near east edge of map, 3.5 km due east of Tortuga Mountain. Age determination # 14 = 32.3 ± 0.3 Ma (SHRMP) (table 1). Thickness 140 m

Tiwm **Ward Mountain pluton (Oligocene)**—Rhyolite pluton, mostly flow-banded rhyolite and fine-grained granite and quartz syenite, contains fine-grained sparsely quartzo-phyric texture with poikolitic amphibole; pluton surrounds west and north sides of The Basin. Age determinations # 20 = 31.5 ± 0.3 Ma, # 21 = 32.4 ± 0.3 Ma, and # 22 = 32.7 ± 0.3 Ma (all SHRMP) (table 1)

Tigr **Granite plutons and stocks (Oligocene)**—Various granite to monzogranite plutons and stocks scattered throughout map; includes a large laccolith in region of Dodson Spring that shows signs of being emplaced as dikes in east and as sills in west (fig. 12). The laccolith is a light gray microgranite comprised of 83 percent feldspar, 8 percent quartz, and 5 percent pyroxene with xenomorphic granular texture according to Lonsdale and Maxwell (1967). Other notable intrusions include Elephant Peak stock, several small intrusions surrounding Dominguez Mountain, two small plutons in Pine Canyon area, and small stocks along Hayes Ridge; not yet dated

Tim **Mafic intrusions of Pine Canyon caldera and Dominguez Mountain (Oligocene)**—Several small mafic stocks in central part of Pine Canyon caldera near Pummel Peak; also a large ring-shaped intrusive body surrounding interior pluton of Dominguez Mountain. Near Pummel Peak Lonsdale and Maxwell (1967) described dark greenish-gray diabase with fine-grained subophitic texture. At Dominguez Mountain dikes are comprised of gabbro that is very porphyritic, containing large euhedral to subhedral grains of white feldspar, with a dark-colored, fine-grained matrix. Not yet dated, but they intrude youngest Pine Canyon fill in Pine Canyon area

Tinm **Intrusions of Nugent Mountain (Oligocene)**—Several small intrusions of porphyritic alkalic rhyolite or micrograrite and alkalic granophyre at and near Nugent Mountain in northeastern part of map. Lonsdale and Maxwell (1967) described alkalic microgranite as comprised of sanidine-anorthoclase and augite phenocrysts in a green groundmass of feldspar laths and alkali feldspar. Dated at 31.5 ± 0.3 Ma on west side of Nugent Mountain

Tipl **Panther laccolith (Oligocene)**—Large laccolith of porphyritic sodic rhyolite north of Pine Canyon caldera. Described as a greenish-gray dense aggregate alkali fieldspar, green clinopyroxene, and 10 percent quartz by Lonsdale and Maxwell (1967). Not dated

Tirs **Rough Spring laccolith (Oligocene)**—Light-gray to dark-gray quartz microsyenite that is also referred to as Government Spring laccolith. Generally hypidiomorphic granular in texture, medium grained, with a salt-and-pepper appearance in hand specimen. Comprised of sanidine-anorthoclase, oligoclase, and quartz. Not dated

Tir **Rhyolite intrusions of Sierra Quemada (Oligocene)**—Small rhyolite stocks in central part of volcanic center at Sierra Quemada

Tetc **Tuff and conglomerate (Oligocene)**—Air-fall tuff and conglomerate at base of eruptive sequence in a very local exposure north of Blue Creek Canyon near west map border. Dated at 32.1 Ma (Ar/Ar) (table 1)

Tsbu **Undifferentiated basalt sills (Oligocene)**—Two exposures of possibly same sill are included in this unit. In both places sill probably originated in Dominguez Mountain volcanic center. Each is a dark-colored basalt that intrudes middle of Chisos Formation in central part of map area along contact between Smoky Creek (above) and Fresno Creek (below) facies groups. Rock is characterized by abundant feldspar laths, which is also typical of many other rocks associated with Dominguez volcano. Determined to be 31 Ma (Ar/Ar; sample # 11) (table 1)

Tdsm **Mafic dikes and sills (Oligocene?)**—Dark colored, probably basaltic in composition, intrudes Chisos Formation east of Pine Canyon caldera at about same stratigraphic interval that Ash Spring Basalt Member (Tfasb) occurs

Tfdmt **Dominguez Mountain core flows (Oligocene?)**—Dark-colored bedded flows in core of Dominguez Mountain (fig. 9). Maxwell and others (1967) described these as layered pyroclastic rocks and lavas that have been thermally metamorphosed to a dense hornfels-like rock. They are probably andesitic to basaltic in composition. Not dated, but are probably Oligocene

Tfdb **Dominguez Mountain basalt(?) flows (Oligocene?)**—Black lava flows on lower east flank of Dominguez Mountain. Identified by unique reflectance characteristics on color air photography. Age and composition not known, probably Oligocene

Chisos Formation and Equivalent Volcanic Rocks (Oligocene and Eocene)

Volcanic-sedimentary facies and temporally equivalent flows of Chisos episode of volcanic buildup.

Tcbr **Breccia facies (Oligocene)**—Breccia and conglomerate in upper part of Chisos Formation just above basalt flow (maybe upper flow unit of Tfbmb) in Wilson Ranch area (fig. 16). Thickness 38 m north of Blue Canyon

Tcwtu **Upper white tuff facies (Oligocene)**—Tuff, sandstone, and rhyolite forming highest facies of Chisos Formation. Generally above basalt flows mapped as Bee Mountain Basalt Member (Tfbmb) in Blue Creek Canyon area

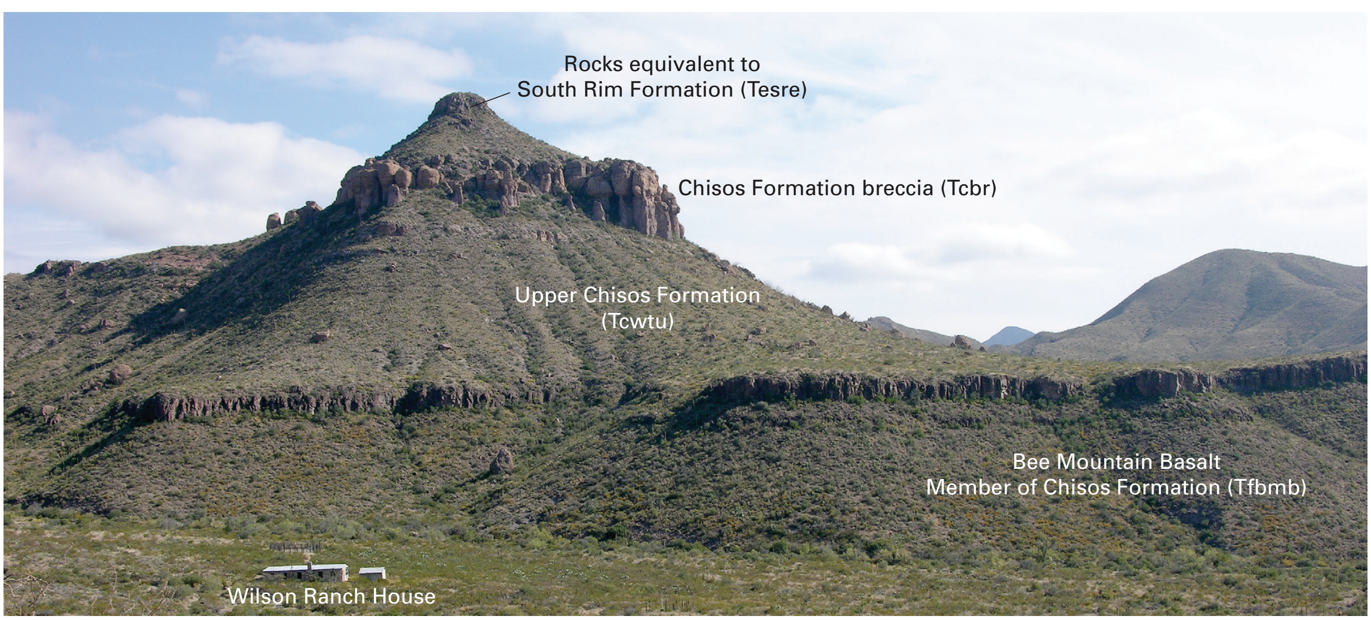


Figure 16. Photograph of small hill east of Wilson Ranch house in Blue Creek Canyon. Bee Mountain Basalt Member of Chisos Formation (Tfbmb) is in lower part of hill below and including small cliff-forming flow.

Tfvt **Vitric tuff (Oligocene)**—Thin vitric tuff northwest of Blue Canyon Ranch just above Bee Mountain Basalt Member (Tfbmb) in Blue Creek Canyon area

Tfbmb **Bee Mountain Basalt Member and equivalent flows (Oligocene)**—Dark-colored basalt flows that are conspicuously scoriaceous. The basalt is mostly fine to medium grained and dark gray in color. Secondary minerals fill many of vesicles, giving rock a mottled appearance. In western part of Chisos Mountains, uppermost flow is distinctly more resistant than those below it, forming a small cliff (fig. 16). Present high in Chisos Formation or just at base of trachyte flows (Tetps), and South Rim Formation rocks and their equivalents. Thickness is variable regionally; 90 m in Blue Creek Canyon area

Tcwt **White tuff facies (Eocene)**—Tuff and tuffaceous sandstone, generally white. Consists of sandstone and air-fall tuff in parallel, continuous beds that are 1–10 m thick. Bedding is much more conspicuous than it is in older facies to east, and this facies is much lighter in color, primarily owing to abundance of tuff, which is commonly white or very light gray (fig. 17). Sandstone and tuff beds have low-angle, internal cross-stratification that suggests that flowing water was an important factor in their depositional history. This unit most likely had a mostly volcanic origin, but reworking in a fluvial environment is likely. Widespread in western part of map south of Ward Mountain, in Sierra Quemada region and south of Punta de la Sierra where it forms lowest unit of Chisos Formation and overlies Alamo Creek Basalt Member (Tfacb). Thickness is greater than 900 m around and west of Sierra Quemada and is about 150 m south of South Rim

Tcksu **Upper siltstone facies (Eocene)**—Greenish, purplish, and gray siltstone, probably derived from shales of Upper Cretaceous Javalina Formation (Kj). Thickness is approximately 200 m south of South Rim

Tfra **Rhyolite ash flow (Eocene)**—Thin, discontinuous rhyolite ash flow interbedded with white tuff facies of Chisos Formation (Tcwt) just west of Juniper Canyon. Thickness is 22 m

Tcyot **Yellow-orange tuffaceous sandstone facies (Eocene)**—Tuffaceous(?) sandstone, distinct yellow-orange color, thick and resistant. Chiefly well bedded. Beds vary between 3–50 cm thick and some are cross-stratified (fig. 18). Most of beds were probably once air-fall tuff, but original grains have probably been reworked by wind and water since their initial deposition. It makes a unique marker horizon in upper part of Chisos Formation at same stratigraphic horizon as a ryholite ash flow

Figure 17. Photograph of white tuffaceous facies of the Chisos Formation (Tcwt) in broad sycline to the east of Castalon highway near west edge of map at about 29° 15′ North.

(Tfra) just west of Juniper Canyon; age determination # 17 = 41.4 ± 0.5 Ma (SHRMP) (table 1). Thickness is 55 to 85 m

Tckss **Tuffaceous sandstone facies (Eocene)**—A small exposure of tuffaceous sandstone; present along west map edge southwest of Punta de la Sierra escarpment. Thickness not known

Tcss **Undifferentiated sandstone facies (Eocene)**—Thin, discontinuous sandstone layers intercalated with white tuff facies (Tcwt) near west and south sides of Sierra Quemada volcanic center. Thickness not known

Tfasb **Ash Spring Basalt Member (Eocene)**—Dark-colored, fine-grained basalt near base of white tuffaceous facies of Chisos Formation (Tcwt) north and west of Chisos Mountain front. Basalt is conspicuously porphyritic in many places with large, white plagioclase laths 1–2 cm in length (fig. 19). Age determination # 26 = 40.38–43.39 Ma (table 1); sampled near highway west of Ward Spring at west map edge. Thickness is 30 to 31 m along northern Chisos Mountain flank

Tfacb **Alamo Creek Basalt Member and equivalent flows (Eocene)**—Dark-colored basalt present beneath Chisos Formation in southwestern part of map. Basal flows are typically scoriaceous, but most of upper flows are dense. Locally some flows are porphyritic and are rich in plagioclase phenocrysts that are as large as 0.5 cm across. Although not dated in

Figure 18. Photograph of typical yellow-orange tuffaceous facies of Chisos Formation (Tcyot) in Blue Creek Canyon.

Figure 19. Photograph of numerous plagioclase crystals in poprphyritic part of Ash Spring Basalt Member of Chisos Formation (Tfasb) near Ash Spring on the northwest flank of the Chisos Mountains. Hammer for scale.

mapped area, elsewhere is about 45.5 to 47 Ma. Thickness 30 to 45 m south of Punta de la Sierra

Tcstr **Sandstone, tuff, and rhyolite facies (Eocene)**—Thick unit of well-bedded brown-colored sandstone with accessory tuffaceous sandstone (fig. 20). Bedding is mostly parallel with even bedding surfaces and uniform bed thickness maintained over large distances. Many beds are cross-stratified internally, others are more massive. Some beds have a conglomeratic base with clasts typically of limestone. Mostly sand grains are quartz, making it hard to determine where original source was, but in some cases fragments of tuff and glass shards are still in evidence, suggesting rivers were probably eroding a nearby volcanic terrain composed mostly of tuff. Present in Fresno Creek area, south of Hayes Ridge, and around circumference of Pine Canyon caldera. Thickness is 690 m

Tcnr **Nodular rhyolite facies (Eocene)**—White rhyolite flows with nodular concretions of quartz ubiquitous, very poorly bedded, and characterized by presence of abundant nodules and irregularly shaped blobs of chalcedony or low-grade agate (fig. 21). Present in Fresno Creek drainage and east and southeast of Pine Canyon area. Thickness is 210 m

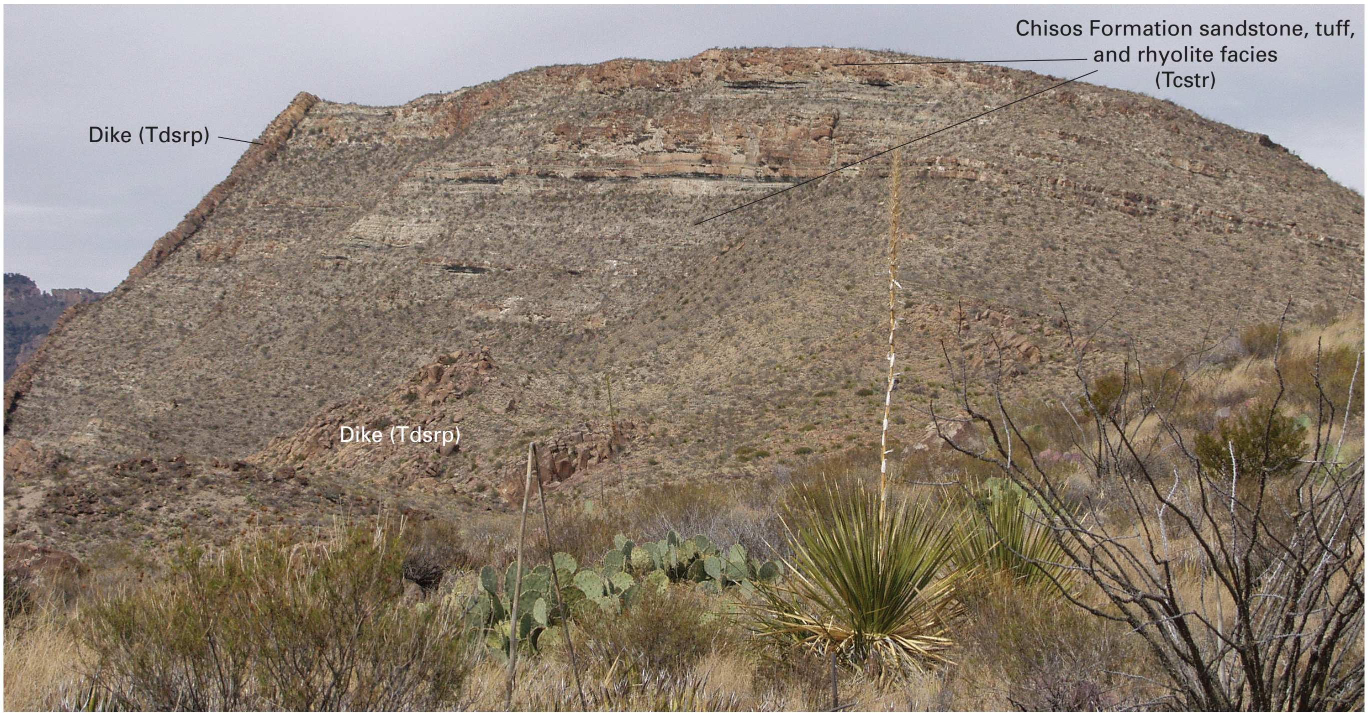


Figure 20. Photograph of a well-exposed section of Chisos Formation sandstone, tuff, and ryholite facies (Tcstr) just to the east of Tortuga Mountain. A large dike of porphyitic rhyolite (Tdsrp) can also be seen.

Figure 21. Photograph of typical exposure of nodular rhyolite facies of the Chisos Formation (Tcnr). White pad in top center shows two scales: 3 in. on the left and 9 cm on the right.

Tcks **Lower siltstone facies (Eocene)**—Interbedded greenish, purplish, and gray siltstone, probably derived from shale of Upper Cretaceous Javalina Formation (Kj); and white to brown quartz-rich beds that are probably altered and silicified air-fall tuff beds (fig. 22). Shows signs of hornfels texture and thermal metamorphism in eastern part of map area. Thickness is variable with a maximum of 175 m near eastern map edge

Tfbu **Basalt flows, undifferentiated (Eocene)**—Basaltic lavas undifferentiated, occur at various stratigraphic horizons within Chisos Formation. One prominent flow sequence occurs in lower parts of Fresno Creek-facies group between siltstone rhyolite tuff (Tcrt) and nodular tuff (Tcnr) facies. This sequence forms a thick and very lenticular body of flows that are dark green-gray to purple-gray basaltic andesite in layers 1–2 m thick. Also contains pods, pockets, and lenses of epidote-rich rock. Several thin sills cut layered sequence at low angles. A new partially analyzed sample age suggests that sills are about 30–31 Ma, but that age probably postdates flows by a considerable amount. Other thin flows are also present in upper parts of Chisos Formation. Thickness variable

Tcl **Lacustrine facies (Eocene)**—Silt and clay, parallel, continuous, and even bedding; consists of interbedded layers of air-fall tuff and siltstone (fig. 23). Tuff and siltstone beds are parallel to one another and are 3–50 cm in thickness. Bedding surfaces are even and beds are very uniform in thickness. Beds of each lithology are internally laminated. Occurs

Figure 22. Photograph of one of the better exposures of the lower siltstone facies of the Chisos Formation (Tcks), which was derived from Cretaceous siltstone exposed nearby.

Figure 23. Photograph of the lacustrine facies of the Chisos Formation (Tcl) showing the thin varve-like laminations that are typical of this facies. Hammer for scale.

beneath undifferentiated basaltic andesite sill (Tsbu) in southeastern part of map near Fresno Creek. Thickness is about 50 m

Tcrt **Rhyolite tuff facies (Eocene)**—Rhyolite and tuff in basal unit of Chisos Formation. Chiefly light pink to light gray rhyolite tuff, characterized by presence of small (1–2 cm) medium-gray globular concretions (fig. 24). Fine-grained to very fine grained, in irregular beds a few centimeters to a few tens of centimeters thick. Most original glass shards are now altered to clay throughout unit. Individual beds are discontinuous, but sub-parallel to one another. Rare sandy lenses as thick as 1–2 m occur locally. Paraconformably overlies metamorphosed Aguja Formation

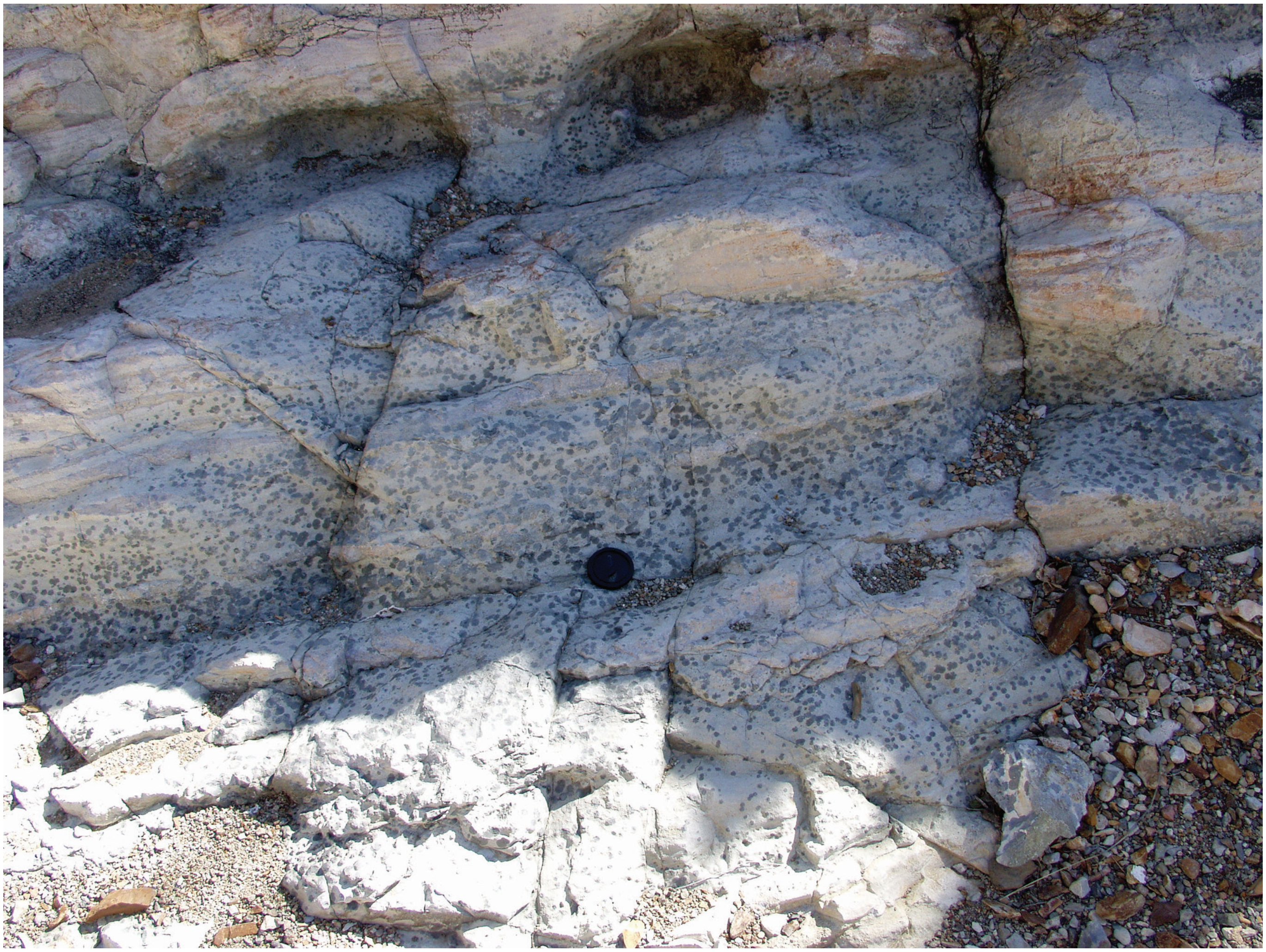


Figure 24. Photograph of the rhyolite and tuff facies of the Chisos Formation (Tcrt) with its characteristic dark-colored nodules. Camera lens cover for scale.

units (Kags); present between Fresno Creek and Dominguez Mountain. Thickness about 65 m

Older Sills (Eocene)

Tsm **Mafic sills**—Dark-colored sills that intrude Cretaceous rocks in southern and northwestern parts of area; might be equivalent to Mariscal Mountain gabbro sill dated at 46.7 ± 0.6 Ma. Thickness is about 60 m

Tsi **Intermediate sill**—Dark-colored basaltic(?) sill intruding Cretaceous rocks in southern part of area. Might be equivalent to Mariscal Mountain gabbro sill dated at 46.7 ± 0.6 Ma. Thickness not known

Marine Seaway Deposits (Paleocene and Cretaceous)

TKbp **Black Peaks Formation (lower Paleocene and Upper Cretaceous)**—Chiefly cross-bedded sandstone, includes some interbedded claystone, similar to upper part of Aguja Formation. Includes a tuffaceous component to claystone more like that of Javelina Formation. Mammal remains and freshwater mollusks are present indicating Paleocene age. Not widely exposed near Chisos Mountains, but is present in small outcrops to northeast and northwest of them. Thickness is 85–265 m regionally (Maxwell and others, 1967)

Kj **Javelina Formation (Upper Cretaceous)**—Claystone containing thin lens-shaped interbeds of buff cross-bedded sandstone. Clay beds are varicolored including brown, green, maroon, and dull gray and are mostly bentonitic, suggesting source of airborne volcanic ash. Bentonite weathers to puffy-textured low ground and dull gray landscape of low hills cut by canyons. Sandstone interbeds are typically cross bedded, ripple marked, and commonly conglomeratic, indicating that they were originally deposited in river channels. Dinosaur bones and fossil wood fragments are common, especially in sandstone, establishing nonmarine nature of formation. Javelina is widely exposed south and northwest of Chisos Mountains. Thickness is 162–285 m regionally (Maxwell and others, 1967)

Kag **Aguja Formation (Upper Cretaceous)**—Claystone that includes thick layers of buff-colored sandstone that are 200–300 m thick in some places. Sandstone is crossbedded and contains ripple marks. Light-gray claystone with concretions, that is similar to claystone in formations above and below, is interbedded with sandstone layers. Lower parts of formation are marine and upper parts are nonmarine. Nonmarine fossils include dinosaur bones, turtle remains, and silicified wood (Maxwell and others, 1967). Aguja is exposed in anticline near Cow Heaven Mountain, along main highway northwest of Chisos Mountains, and at several locations in The Basin. Probable Aguja Formation is also exposed in core of a structural dome near Tortuga Mountain. Nautilus fossils have been identified from Aguja indicating that it is marine in origin. Thickness is 232 to 354 m regionally (Maxwell and others, 1967)

Kags **Metamorphosed sandstone or quartzite facies near Tortuga dome**—Arkosic metasandstone and quartzite. Detrital sand grains of zircon have been dated and youngest of these is 76.8 Ma, which is a minimum age

Kaghf **Hornfels facies**—In Tortuga dome, Aguja Formation has been slightly metamorphosed, causing it to have a different appearance than it does elsewhere (fig. 25). Metamorphism is thermal in nature, caused by heat from a thick sill of granodiorite and possibly a small granite pluton that intruded formation locally. Light-gray claystone has been changed into dark red-brown hornfels and sandstone into quartzite by this metamorphic process. Hornfels is hard and resistant, unlike its protolith (parent rock), and it forms steep cliffs

Kp **Pen Formation (Upper Cretaceous)**—Primarily claystone that includes thin parallel interbeds of fine-grained sandstone. Maxwell and others (1967) described it as weathering light yellow-gray in most places. Concretions are common and most of them are cemented by calcite, others by iron. Pen is marine in origin, and fossil ammonites and pelecypods are abundant. The claystone is not resistant, so unit commonly forms lowlands with smooth, soft-looking slopes on hillsides. A small exposure of Pen occurs west of Emory Peak, and it is exposed in core of anticline near Cow Heaven Mountain, otherwise it is not present in Chisos Mountains. Thickness is 140 m regionally (Maxwell and others, 1967)

Kb **Boquillas Formation (Upper Cretaceous)**—Thin-bedded limestone, chalk, and marl; resistant limestone beds commonly weather into thin flagstone sheets. There is typically more chalk and marl than flagstone, and chalk beds form resistant ledges. Although Maxwell and others (1967) subdivided Boquillas into members, no attempt has been made to differentiate these in Chisos Mountains. Their upper member, San

Vincente Member, is probably only one exposed in Range. Boquillas is chiefly a marine unit that formed in Cretaceous seaway. Numerous species of nautilus and ammonite, as well as fish bones, shark teeth, and mosasaur remains have been reported from it (Maxwell and others, 1967). Only places formation is exposed in Chisos Mountains are in The Basin and Laguna Meadow areas. Thickness of upper Boquillas (San Vincente Member) is about 120 m regionally (Maxwell and others, 1967)

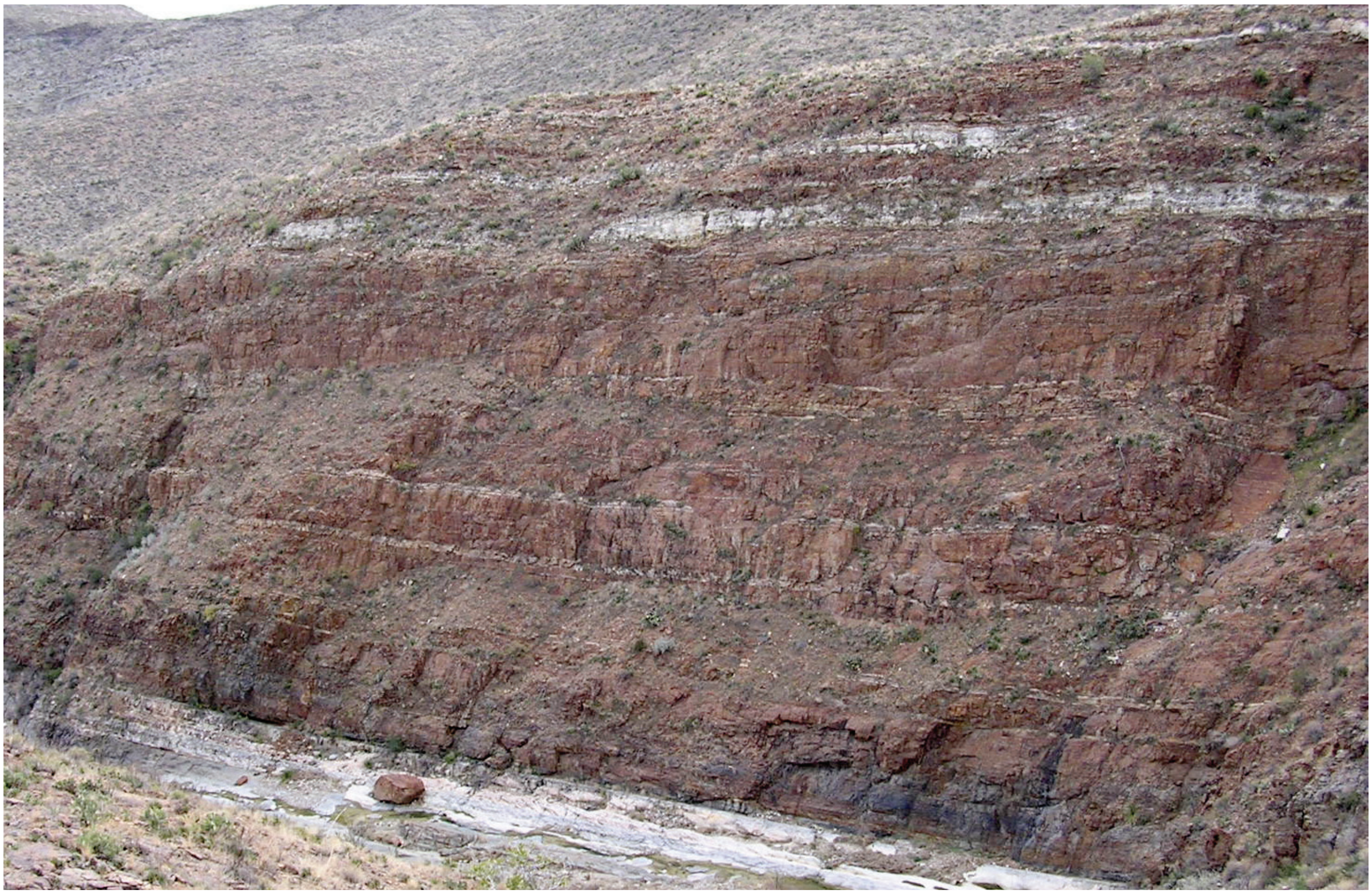


Figure 25. Photograph of mudstone of the Aguja Formation (Kaghf) that has undergone a slight thermal metamorphism to hornfels in Fresno Creek near Tortuga Mountain.

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