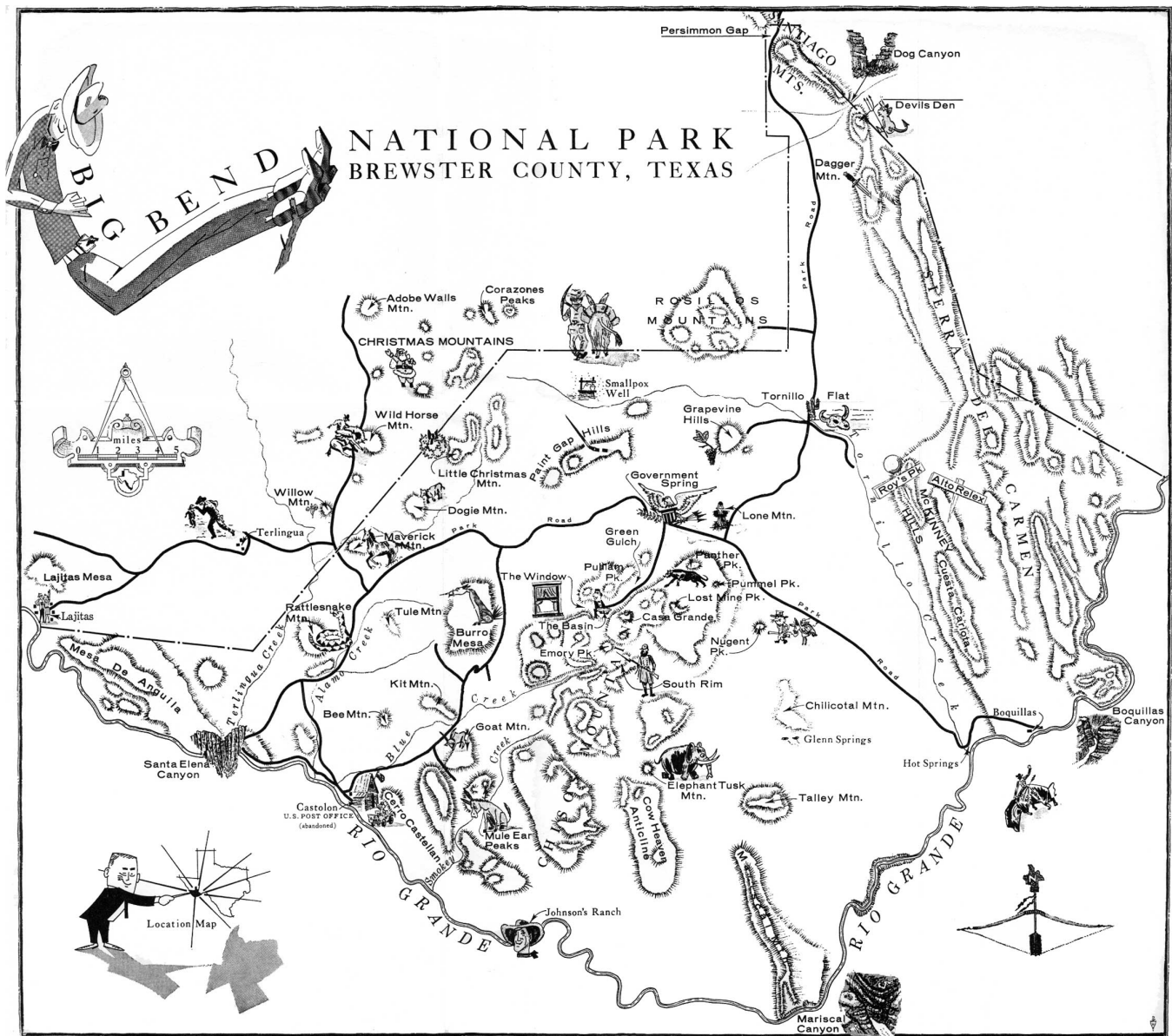


Big Bend National Park

Geologic and Soil Resources Inventory Summary



On this page: Illustration of Big Bend National Park with principal geologic and topographic features. Figure 4 from Maxwell (1968).

Big Bend National Park

Geologic and Soil Resources Inventory Summary

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Abstract

This document summarizes the status of National Park Service (NPS) Geologic Resources Inventory (GRI) and Soil Resources Inventory (SRI) deliverables for Big Bend National Park. It also provides information on current geology and soil resources management concerns, with a focus on identified inventory needs related to geologic heritage, geohazards, and related soil features and processes. This document is intended to assist park staff with prioritizing technical assistance or new inventory and assessment funding requests in the near term (roughly 1–5 years).

The GRI hosted a baseline scoping meeting for Big Bend National Park in 2002. Baseline bedrock and surficial geologic maps were delivered to the park in 2011. SRI delivered a legacy soil database and map to the park in 2007, published an “enhanced report” in 2011, and updated the soil database in 2013.

Big Bend National Park’s geologic heritage is engrained in its diverse stratigraphic, tectonic, and paleontological records, Indigenous connections, mining history, stratotypes, and connections to NASA mission trainings. The geologic and soil resources inventory needs for the park include various data and/or GIS needs related to the inventory and monitoring of cultural resources, fossils, stratotypes, cave and karst features, hydrological systems, hydrocarbon development, soils and soil erosion, climate change, and geoscience research.

Geologic hazards identified in the park include flooding, disturbed lands (e.g., historic ranch lands, abandoned mineral lands), mass wasting (e.g., rockfalls, landslides), swelling clays, seismicity, radon, toxicological soils, and climate change. Inventory needs related to geohazards address monitoring strategies to help quantify and mitigate the damage these processes pose to the park’s geologic and soil resources.

Additional guidance for park staff regarding proposal processes and timeframes for the new Inventories and Assessment (I&A) program is available on the [GSRI](#) and [I&A](#) SharePoint sites.

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Introduction

Background to the GSRI

In the 1990s, the NPS Geologic Resources Inventory (GRI) and Soil Resource Inventory (SRI) programs were established as two of the original 12 baseline inventories in the Inventory and Monitoring (I&M) program. These baseline inventories compiled existing information, acquired new information, and helped establish a minimum level of data across more than 270 parks, which served as a common starting point for natural resource monitoring. For both the GRI and SRI, the primary deliverable was a digital (GIS) map. Between the 1990s and early 2020s, GRI scoping summaries, geologic map posters, and GRI reports were also produced for most of the 270 parks. As of 2024, the I&M program is transitioning from a baseline inventory strategy to a park-proposed, management-need-focused inventory strategy.

The GRI and SRI are now unified as one inventory program, the Geologic and Soil Resources Inventory (GSRI). The new GSRI guidance is projected to be enacted in 2025 for FY2027 funding proposals. In this transition period before the new guidance is completed, 13 “priority” parks, including Big Bend National Park, were identified as missing a baseline GRI report.

This GSRI summary serves as a substitute for a baseline GRI report and is intended to support the national park’s participation in the new inventories program. As such, it summarizes the status of GRI and SRI deliverables for BIBE and provides information on current geology and soil resources management concerns with a focus on identified inventory needs. Information in this summary was compiled from existing reports, meetings with park staff, and the best professional judgment of GRI and WASO Geologic Resources Division (GRD) geoscientists.

Park Establishment and Setting

Big Bend National Park (“BIBE,” also referred to as the “national park” herein) lies along the US–Mexico border at the southernmost tip of Trans-Pecos Texas in Brewster County, southwest Texas (Figure 1). The national park was established 20 June 1935 and encompasses approximately 324,219 ha (801,163 ac). Mountains contrast with desert within the great bend of the Rio Grande, with an elevation of less than 549 m (1,800 ft) along the river valley to 2,385 m (7,825 ft) in the Chisos Mountains. The natural beauty of BIBE includes massive canyons, vast desert expanses, volcanic landscapes, sky islands (isolated, forested mountains), and an ever-changing river system. The national park was designated a Biosphere Reserve in 1976.

The geology of the BIBE is complex, as the region has hosted a diversity of depositional environments coupled with multiple tectonic events. A wide variety of sedimentary, volcanic, and intrusive rocks are exposed in the national park, and the span of geologic time represented by them extends from the early Paleozoic Era to the Quaternary Period (~485 million years ago to the present; Maxwell et al. 1967; Turner et al. 2011; see <https://stratigraphy.org/chart>; accessed June 2024). However, many of BIBE’s chaotic, disturbed landscapes are composed of rocks dating to the Cretaceous Period or younger. Throughout much of the Paleozoic Era, the Big Bend area was occupied by an ancient ocean that subsequently disappeared as two large land masses collided to form the Ouachita Mountains. Shallow seas flooded the national park region during the Cretaceous Period but began to retreat as a second mountain-building event occurred that resulted in large-scale uplifts of rock that formed the Rocky Mountains. Regional crustal extension (pulling apart of Earth’s crust) resulted in several volcanic eruptions and the development of vertical faulting around 30 million years ago. The subsequent history of BIBE is primarily one of erosion, with the Rio Grande carving deep, steep-walled canyons along the folded strata and tilted fault blocks (Maxwell et al. 1967).

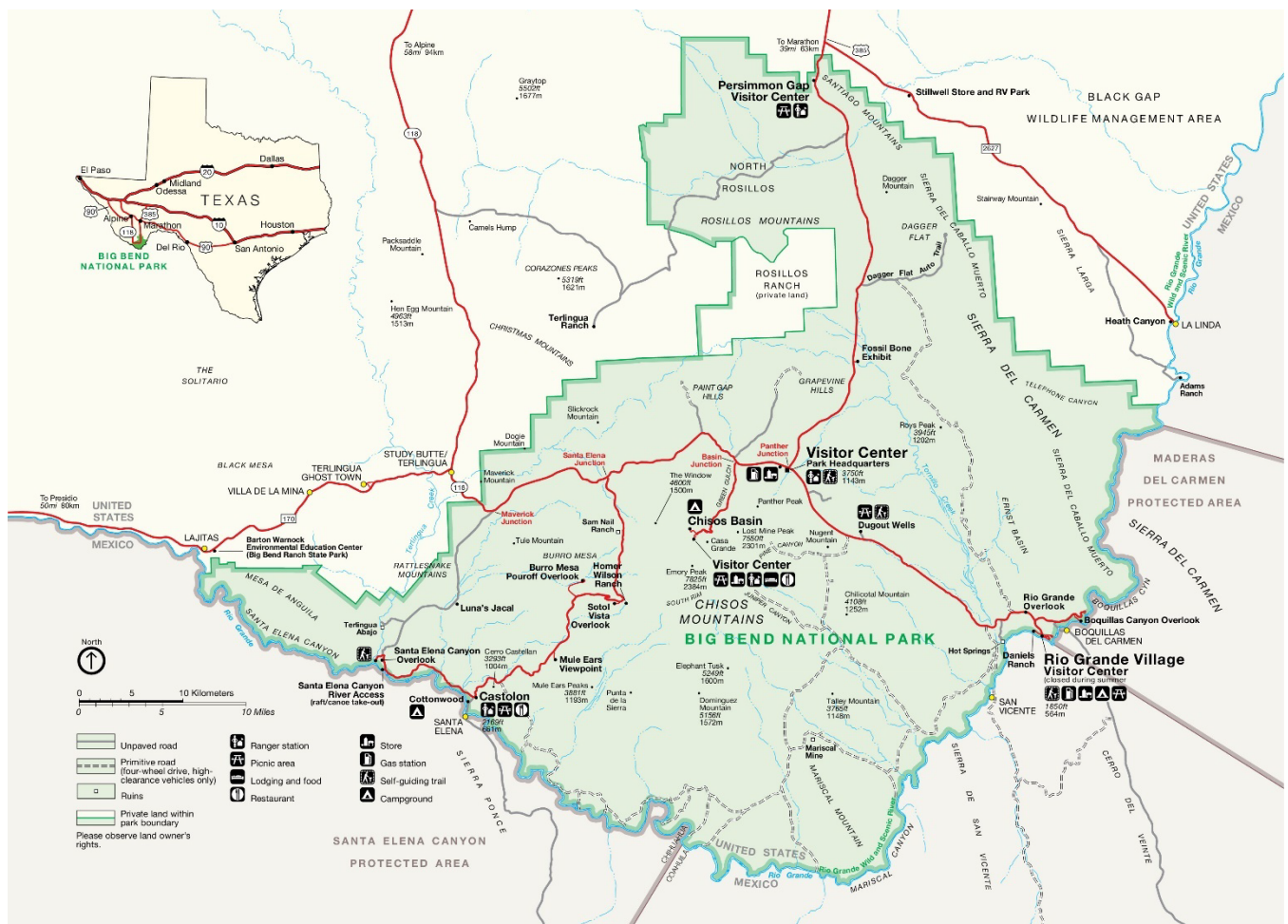


Figure 1. Map of Big Bend National Park, Texas. National Park Service maps are available at www.nps.gov/carto.

Geologic Heritage

Geologic heritage (also called “geoheritage”) evokes the idea that the geology of a place is an integral part of its history and cultural identity. In 2015, the National Park Service's GRD, in cooperation with the American Geosciences Institute, published a booklet introducing the American experience of geoheritage, geodiversity, and geoconservation: *America's Geologic Heritage: An Invitation to Leadership*. This publication introduces key principles and concepts of America's geoheritage, which are the focus of ongoing collaboration and cooperation on geologic conservation in the United States. That booklet introduced the American experience of geologic heritage and outlined key principles and concepts, including the following five big ideas:

- America’s geologic landscape is an integral part of its history and cultural identity, and Americans have a proud tradition of exploring and preserving geologic heritage.
- America’s geologic heritage, as shaped by geologic processes over billions of years, is diverse and extensive.
- America’s geologic heritage holds abundant values—aesthetic, artistic, cultural, ecological, economic, educational, recreational, and scientific—for all Americans.
- America’s geologic heritage benefits from established conservation methods developed around the world and within the United States.
- America’s geologic heritage engages many communities, and involvement by individuals will ensure its conservation for future generations.

Major Tectonic Episodes

The geologic history of BIBE records four significant tectonic episodes that formed the iconic landscape, including its fault block ridges, volcanic ranges, and massive canyons: the Marathon orogeny (which created the southwestern equivalent of the Appalachian Mountains), Mesozoic rifting (which opened the Gulf of Mexico), the Laramide orogeny (which created the modern Rocky Mountains), and crustal extension that formed the Basin and Range physiographic province extension (Figure 2). These regional events influenced the geologic evolution of the national park as well as large areas of the western United States. Although the oldest strata exposed in BIBE are Paleozoic rocks, its geologic history spans over a billion years and includes rifting events dating back to the Proterozoic Eon. Older, buried fault structures extend across west Texas into Mexico and may have been zones of weakness that influenced the long-term geological evolution of the national park’s landscape (see “Structural Geology”; Turner et al. 2011).

Marathon Orogeny

Some of the oldest geologic structures in the national park are thrust faults formed during the Middle Mississippian to Early Permian (approximately 330 million to 285 million years ago) Marathon orogeny, a mountain-building event that resulted from the collision of the North American and South American tectonic plates (Page et al. 2008; Atkinson 2016; Turner et al. 2011). Uplifted rocks of the Marathon orogenic belt represent an extension of the larger Ouachita-Marathon-Sonora orogenic belt that extends along the Paleozoic continental margin from Mississippi and Arkansas (Ouachita segment), through Texas (Marathon segment), and into Chihuahua and Sonora, Mexico (Sonora segment; Turner et al. 2011). During the orogeny, deep marine sedimentary rocks deposited south of BIBE were thrust northwestward onto the North American continental margin (Figure 3). The Marathon orogeny represents one of several collisional events that culminated in the formation of the supercontinent Pangea.

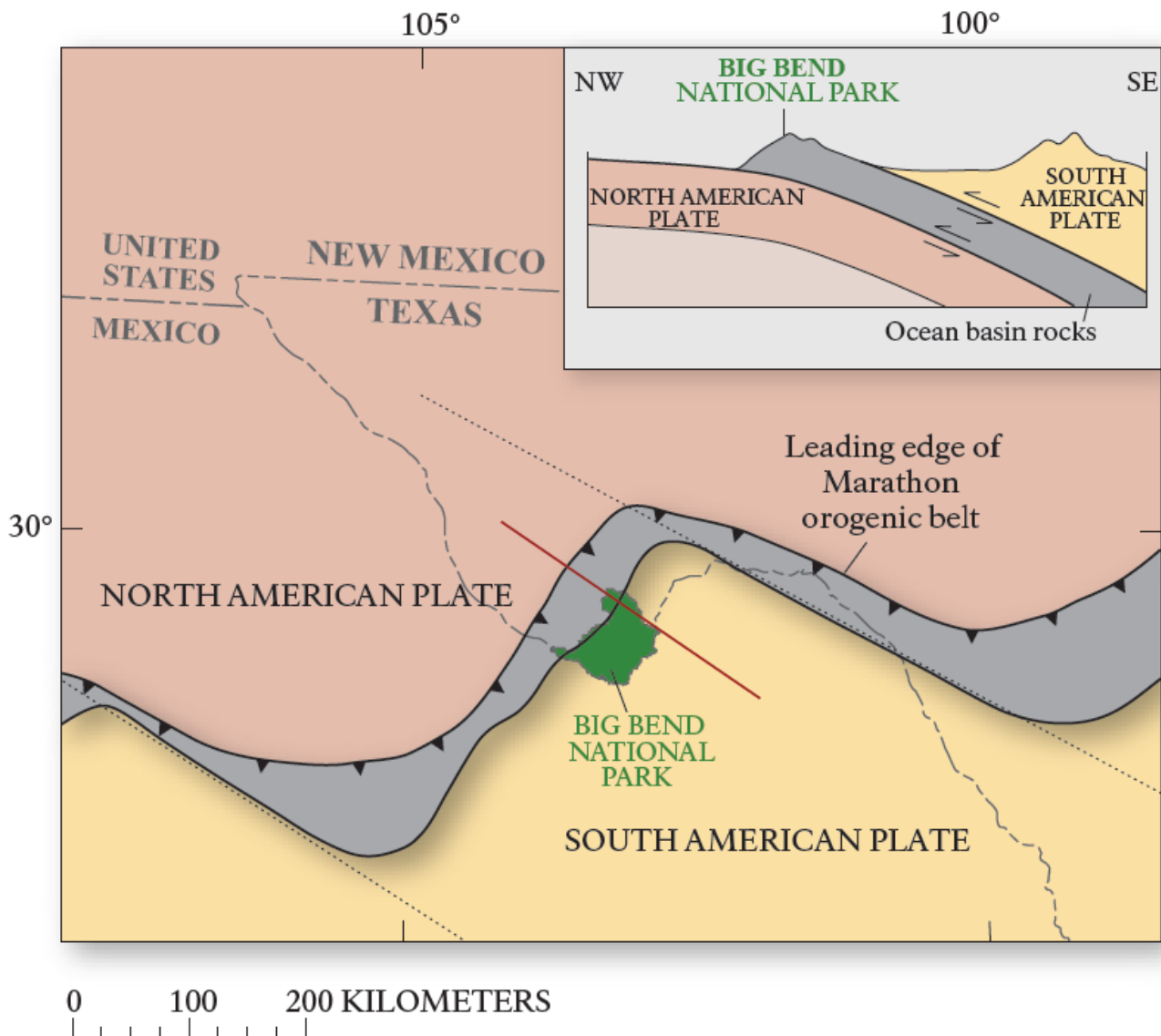


Figure 3. Map of the Paleozoic Marathon orogenic belt. Map shows the location of the orogenic belt (gray) that formed from the convergence of the North and South American plates. The collision thrust marine sedimentary rocks onto the southern margin of the North American plate, as depicted in the inset figure. Dotted black lines are traces of Proterozoic basement faults. Solid red line is an approximate line of cross-section for the inset figure. Figure 10 from Turner et al. (2011).

Paleozoic rocks associated with the Marathon orogeny include the following (in chronological order): (1) Middle to Upper Ordovician Maravillas Formation (**MOu**); (2) Silurian to Mississippian Caballos Novaculite (**MOu**); and (3) Mississippian–Pennsylvanian Tesnus Formation (**PNMt**). Today, remnants of these marine strata can be observed in folded and faulted exposures near Persimmon Gap and Dog Canyon in the northern area of the national park. More information about these geologic units can be found in the “Geologic Themes and Prior Work” section of this report.

Following the Marathon orogeny, regional uplifts were slowly eroded from the Triassic through Jurassic Periods, as recorded by a major unconformity (a gap in the rock record representing periods of erosion or nondeposition) separating the Cretaceous Glen Rose Limestone from underlying Paleozoic rocks (see “Unconformities”).

Mesozoic Rifting

From the Late Triassic to Late Cretaceous (about 200 million to 85 million years ago), the Big Bend area was subtly affected by rifting events that controlled the opening of the Gulf of Mexico (Page et al. 2008; Turner et al. 2011). During these rifting events, BIBE was part of the Diablo platform, a shallow, open-marine shelf environment located adjacent to a newly formed ocean basin referred to as the Chihuahua trough (Figure 4). Several Lower and Upper Cretaceous formations—notably the park’s massive carbonate sequences—were deposited during this time and include the following (in order from oldest to youngest): Glen Rose Limestone (**Kgr**), Maxon Sandstone (**Ktm**), Telephone Canyon Formation (**Ktm**), Del Carmen Limestone (**Kdc**), Sue Peaks Formation (**Ksp**), Santa Elena Limestone (**Kse**), Del Rio Clay (**Kdr**, **Kbd**), Buda Limestone (**Kbu**, **Kbd**), Boquillas Formation (**Kb**, **Kbe**, **Kbs**), and Pen Formation (**Kp**). Deposition of the Upper Cretaceous Aguja (**Ka**) and Javelina (**Kj**) Formations marks a significant shift from marine to continental (coastal and fluvial) deposition in response to infilling of the Chihuahua trough and the onset of the Laramide orogeny. More information about these geologic units is in the “Geologic Themes and Prior Work” section of this report.

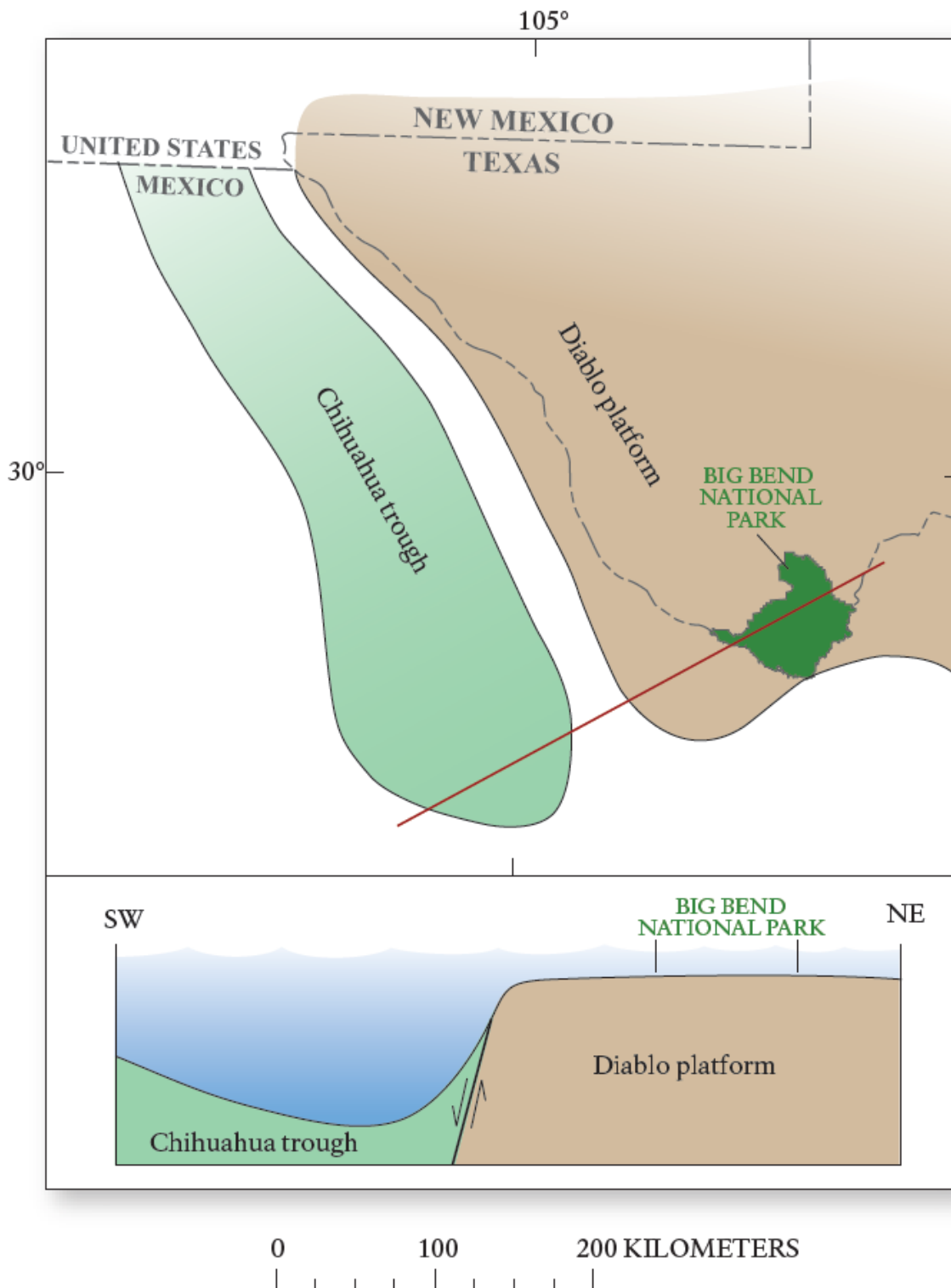


Figure 4. Map of the Diablo platform and Chihuahua trough. Map shows the location of the national park relative to the Diablo platform and Chihuahua trough. During the Late Triassic through Late Cretaceous Periods, the Big Bend area experienced rifting related to the separation of the North and South American plates. Solid red line is the approximate line of section for inset cross-sectional figure. Figure 11 from Turner et al. (2011).

Laramide Orogeny

The Late Cretaceous–early Tertiary (approximately 70 million to 50 million years ago) Laramide orogeny was a period of compressional deformation related to the shallow subduction of the Farallon plate beneath the western margin of North America (Page et al. 2008; Turner et al. 2011; Atkinson 2016). Plate convergence formed the extensive Cordilleran overthrust belt that extends across the American intermountain region from Canada to Mexico, as well as the Laramide foreland basin east of the overthrust belt. Deformation associated with the Laramide orogeny overprinted earlier geologic structures related to the Marathon orogeny and likely produced many of the monoclinical uplifts, basins, and faults throughout the national park, including the Mesa de Anguila monocline, Terlingua monocline, Sierra del Carmen–Santiago Mountains monocline, Tornillo basin, Mariscal Mountain and Cow Heaven anticlines, and the Santiago thrust (Figure 5; see “Faults” and “Folds”).

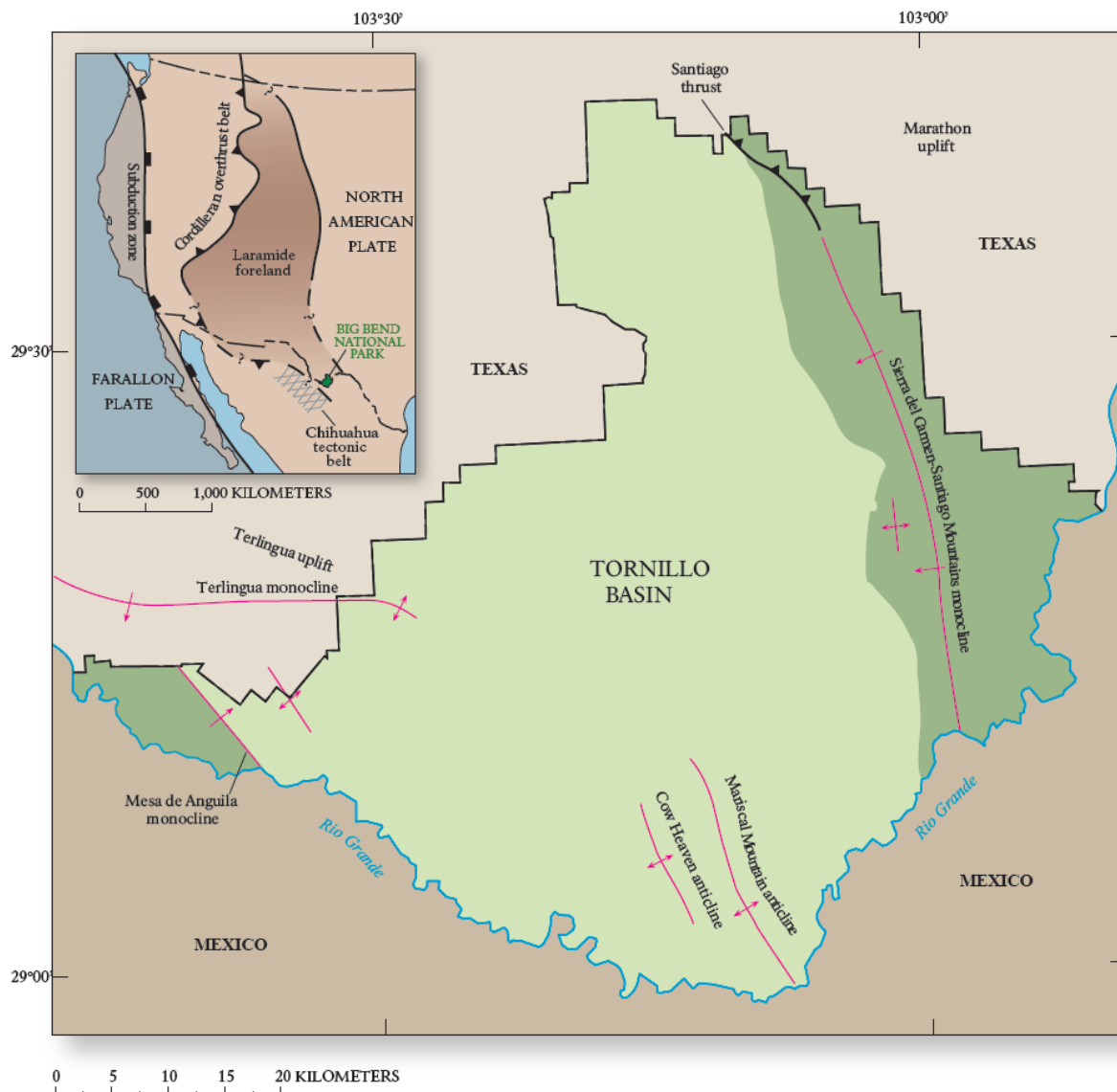


Figure 5. Map of geologic structures in the Big Bend area. Map shows the major geologic structures that formed in the Big Bend area during the Laramide orogeny. Inset map shows the configuration of the North American and Farallon plates, in addition to the subduction zone along the western North American continental margin, the Cordilleran overthrust belt, the Laramide foreland, and the national park location (dark green). Figure 12 from Turner et al. (2011).

Basin-and-range Extension

The last major tectonic episode recorded within the national park is the development of the Basin-and-Range physiographic province that occurred during the late Tertiary (Oligocene to Pleistocene Epochs) approximately 25 million to 2 million years ago (Turner et al. 2011). Large-scale crustal extension and thinning (also referred to as “basin-and-range extension” or “basin-and-range faulting”) created a structural landscape defined by horsts (an uplifted block bounded by high-angle normal faults) and grabens (a subsided trough or basin bounded by high-angle normal faults). The development of several high-angle normal faults has created fault block ridges (ex: the Sierra Del Carmen) but also controlled the evolution of local depositional basins such as the Estufa and Delaho bolsons (basins) that flank the Chisos Mountains. As headwall blocks (downthrown side of a normal fault) subsided, these depositional basins accumulated a thick sequence of Miocene to Pleistocene sediments (Figure 6; see “Extensional Basins”). Basin-and-range faulting predates the integration and through-flow of the Rio Grande, which took place during the Pleistocene Epoch around 2 million years ago (Page et al. 2008; Turner et al. 2011).

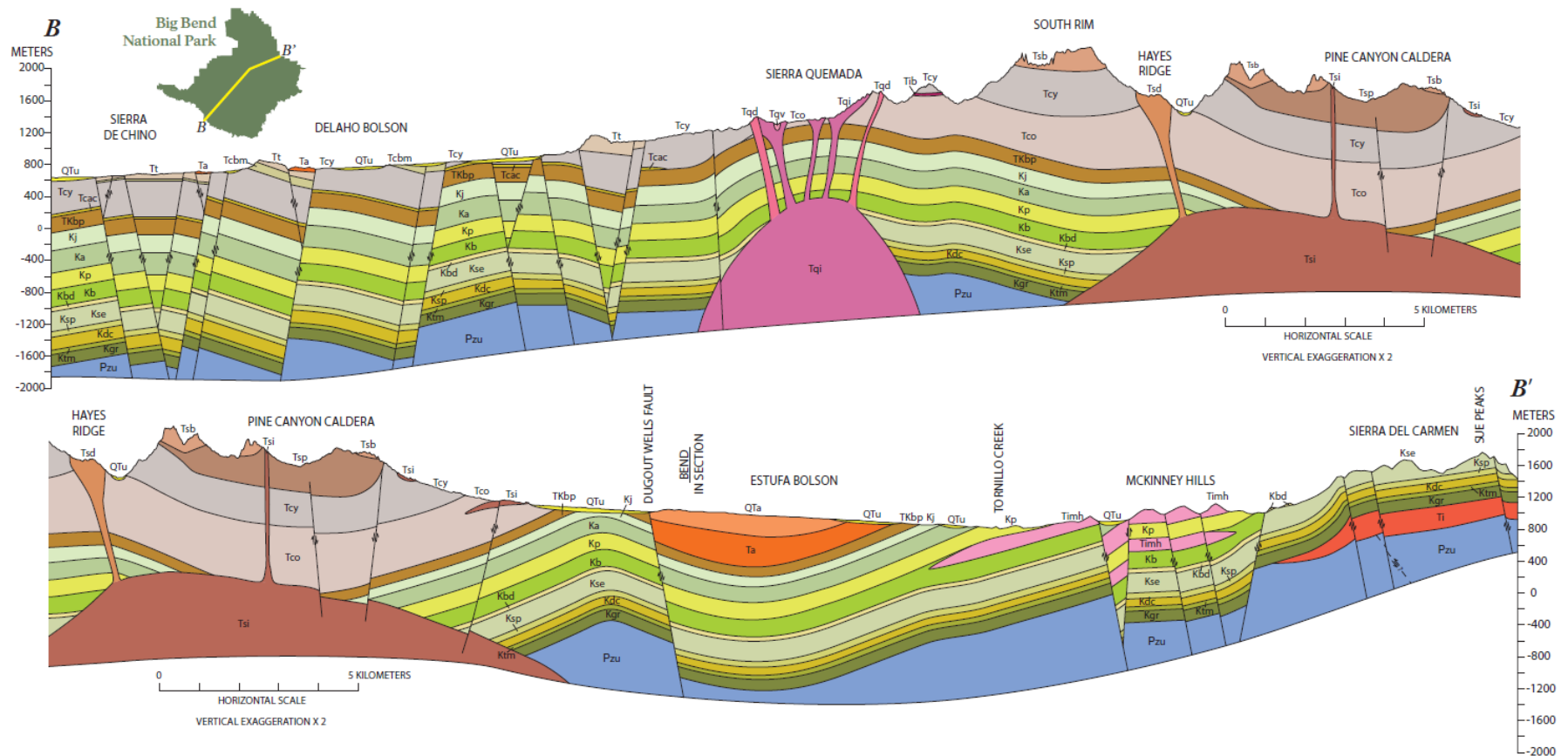


Figure 6. Geologic, cross-section of BIBE from Sierra de Chino to Sierra del Carmen. The national park's landscape has been heavily influenced by Laramide compression, Tertiary volcanism and plutonism, and basin-and-range extension. Numerous high-angle normal faults dissect BIBE and have produced several local extensional basins, such as the Delaño and Estufa bolsons that flank the Chisos Mountains. Inset map of the national park shows the approximate line of cross-sectional traverse. Figure from Turner et al. (2011), modified by Tim C. Henderson (Colorado State University).

Dinosaurs, Mammals, and the K–Pg Boundary

Big Bend National Park is a premier locality to study the Cretaceous–Paleogene (“K–Pg”; formerly regarded as the Cretaceous–Tertiary “K–T” boundary) mass extinction event that ended the reign of the dinosaurs and heralded the age of the mammals. Within BIBE, the strata of the Cretaceous–Paleocene Black Peaks Formation (**TKbp**) record an uninterrupted interval of Earth history encompassing the K–Pg transition and are unique in that they are some of the few non-marine deposits in proximity to the asteroid impact site along the Yucatan Peninsula (Santucci et al. 2018). Rocks preserved along the K–Pg boundary in Big Bend contain a wealth of isotopic, biochronological, and palynological data that may help further explain the nature of the extinction event, including global transformations in climate and evolutionary response (Wick and Corrick 2015). Although the K–Pg extinction horizon is marked by a distinct iridium-rich sediment layer in other parts of the world, the boundary recorded at the national park contains only a hint of the iridium anomaly—an enigma that merits further research.

Deposits of the Aguja (**Ka**), Javelina (**Kj**), Black Peaks (**TKbp**), and Hannold Hill (**Khh**) Formations include a plethora of paleontological resources that record the demise of the dinosaurs and the evolutionary radiation of mammals from tiny insectivores to primitive primates (see “Paleontology”; Wick and Corrick 2015).

Big Bend, NASA, and Apollo Mission Trainings

In the 1960s and 1970s, BIBE was one of several national park units used by the National Aeronautics and Space Administration (NASA) to train astronauts and test spacecraft in preparation for human space exploration. Astronauts within NASA’s Apollo program often traveled to “analog sites” comparable to the Moon’s landscape to study various rock types, practice field communication, and experience extreme environments. Apollo astronauts visited the national park numerous times (spring of 1964, 1968, and 1969; fall of 1971) to study volcanic rocks, interpret stratigraphy, perform geologic mapping, collect samples, take photos, and give verbal descriptions (Phinney 2015). An excerpt of the 1964 trip is described by Dr. Elbert A. King, Jr., a professor of geology at the University of Houston who helped with the field investigation:

Like the Grand Canyon, Big Bend is a beautifully wild place, particularly in the springtime before the full heat of summer arrives... There were many lessons to learn in Big Bend. One was discovered by Neil Armstrong, who hit a basalt outcrop with his rock hammer and was cut slightly on the arm by a flying rock chip. This was not the correct way to collect rock samples, either on the Earth or the Moon. Even a small cut in a space suit could have serious consequences (King 1989, p. 31–33).

Stratotypes

Stratotypes are important geologic reference exposures that help identify, define, and correlate geologic units from one location to another. When geologists propose or describe a new layer or body of rock, a stratotype is assigned to exposures containing all (or most) of the unique diagnostic criteria. Stratotypes have significant scientific value and are often easily accessible, world-class locations to study outcrops of rock. Akin to natural libraries of Earth history, stratotypes preserve meaningful clues to the past and serve as geologic classrooms (Henderson et al. 2023). The stratotype concept is engrained in the modern system of geologic nomenclature, as many formal geologic unit names are derived from geologic or geographic features found near stratotype locations. Some particularly recognizable examples from within the National Park System (and their stratotype assignments) include the Permian De Chelly Sandstone (Canyon de Chelly National Monument, Arizona), the Cretaceous Mesaverde Group (Mesa Verde National Park, Colorado), and the Pleistocene Valles Rhyolite (Valles Caldera National Preserve, New Mexico). More information about the various kinds of stratotypes (i.e., lithostratigraphic versus chronostratigraphic) and how to propose or

modify them can be found in the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature 2021) as well as Stamm (2023).

Big Bend National Park contains 46 stratotypes that represent a diverse mosaic of Cretaceous and Tertiary geologic units. Many of these were assigned by Ross Maxwell, the first superintendent of BIBE (Henderson et al. 2021; Henderson et al., in review). In honor of Maxwell's service, contributions, and support, the 48 km (30 mi) road extending across the western side of the park to reach the Castolon Historic District and Santa Elena Canyon is named the Ross Maxwell Scenic Drive.

Mining

The national park has a long, colorful mining history, and partially substantiated stories have inspired legends such as the lost silver and gold mine (hence, the Lost Mine Trail and Lost Mine Peak) high in the Chisos Mountains (Maxwell 1968). Although the Big Bend region is known to contain commodities including mercury, fluorine, and uranium, the only significant mining within BIBE has been for mercury. Mercury mining was prevalent by the late 19th century and continued intermittently until about 1973 (Gray et al. 2008). Today, mercury contamination presents a potential hazard (see "Abandoned Mineral Lands"). To the west of BIBE, the Terlingua mining district includes more than 30 abandoned mines located along the drainage of Terlingua Creek. At the northern end of the Mariscal Mountains, D. E. Lindsey operated a small quicksilver or cinnabar (ore containing mercury) prospect about 13 km (8 mi) north of the Rio Grande. According to Maxwell (1968), a small, low-grade fluorite deposit occurs near the top of the Lower Cretaceous limestone, about 1.6 km (1 mi) south of the old mine.

Historically, deposits of copper, lead, zinc, and silver ore were mined a few miles southeast of Boquillas in Coahuila, Mexico. The ore was hauled by mule teams north through Persimmon Gap and on to Marathon. Additionally, caves within BIBE were mined for bat guano during the early part of the 20th century (Atkinson 2016).

Indigenous Connections

Scattered across the national park are thousands of archeological sites, some of which record ancient human cultures and encompass several Indigenous groups such as the Chisos (whom the Chisos Mountains are named after), Mescalero, Apache, and Comanche (National Park Service 2016; Atkinson 2016). Although only 10% of BIBE has been surveyed for cultural resources, nearly 3,000 sites have been inventoried that date back to the Paleo-Indian period (13,500 years before present; National Park Service 2018). Indigenous resources considered invaluable to Big Bend's cultural history and identity are preserved across the national park's geologic landscape and include features such as cave and rock shelters, mortar holes, mining and acquisition sites, burn rock midden/roasting pits, hearths/hearthstones, lithic workshops, stone tools, and petroglyphs/pictographs (Maxwell 1968; Bousman and Rohrt 1974; Atkinson 2016; National Park Service 2018). Lithic resources were important to Indigenous Peoples, and they are known to have exploited a variety of rock types in what is now the national park. Preferred raw material sources for stone tools include a large chalcedony deposit on Burro Mesa, silicified fossil wood, and hornfels (a fine-grained metamorphic rock created by contact metamorphism). Several factors, such as erosion, weathering, vandalism, looting (illegal collecting), flooding, collapse, and benign neglect, threaten the archeological resources of the national park (see "Geologic Resource Protection"). Today, BIBE staff members consult with 17 tribes affiliated with the Big Bend region or having traditional ties to the area; the closest tribe to the national park is approximately 483 km (300 mi) away (National Park Service 2018).

Other Notable Figures to Big Bend

The early exploration and history of BIBE includes several notable scientific figures. Beginning in the mid-19th century, one of the earliest records of exploration in the Big Bend region is the account of US Army

Major William H. Emory, a soldier and scientist who led the Mexican Boundary Survey of 1848–1853 (Wick and Corrick 2015). Today, Emory Peak (the highest peak in BIBE and the third highest in Texas) is named in his honor. At the end of the 19th century, US Geological Survey (USGS) geologist Robert T. Hill led a small expedition through the canyons of the Rio Grande from Presidio to Langtry, Texas. Hill documented and photographed the canyons of the Rio Grande and later published an article describing his month-long journey. In the early 20th century, Johan A. Udden described the stratigraphy and paleontology of the Big Bend region. Regarded as the “father of sedimentology” in North America, Udden was one of the first scientists to describe the “sunken block,” the two half-grabens formed during Basin and Range extension that transect the national park (see “Basin-and-range Extension”).

As the first superintendent of the national park, Ross Maxwell contributed greatly to the geological and paleontological framework of the area, including many of its stratotype designations (see “Stratotypes”). Successful dinosaur prospecting within BIBE in the early 1930s attracted the attention of Barnum Brown, considered to be one of the greatest and most successful paleontologists of the 20th century, who is credited with discovering the first *Tyrannosaurus rex* within the Cretaceous Hell Creek Formation in Montana. In the summer of 1940, Brown spent the summer collecting several interesting and notable fossil specimens throughout the national park, including partial jaw bones of the supercrocodile *Deinosuchus*, a crushed skull of an ankylosaur, and partial ceratopsian and hadrosaur remains, in addition to *Alamosaurus* bones (Wick and Corrick 2015). During the 1990s, Dr. Walter Alvarez visited BIBE in search of the iridium-bearing strata recorded in the K–Pg boundary (see “Dinosaurs, Mammals, and the K–Pg Boundary”). Alvarez and his father are credited with the discovery of the iridium anomaly produced by the meteorite impact that caused the extinction of the dinosaurs at the end of the Cretaceous Period.

Geologic Themes and Prior Work

Bedrock and Surficial Geology

The following geologic time scale (Table 1) puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. Likewise, rocks and unconsolidated deposits are listed stratigraphically, with stratotype designations italicized and underlined (see “Stratotypes”).

Information in the following geologic time scale, including timing of geologic events, is primarily from Maxwell et al. (1967) and Turner et al. (2011).

Table 1. Geologic units mapped within the national park.

GSRI map abbreviations for each time division and GSRI map unit symbols are in parentheses. Units with stratotype designations within the national park are underlined and italicized. Only geologic units mapped within BIBE are included. Boundary ages follow the International Commission on Stratigraphy (2023).

Geologic Time Unit	Age	Geologic Units (GSRI map symbol)	Geologic Events
Quaternary Period: Holocene (H) Pleistocene (PE)	2.58 million years ago to present	Active tributary and river deposits (Qaw) Axial river deposits (Qyw1, Qyw2, Qiw, Qiw1, Qiw2, Qiw3, Qow) Alluvial deposits (Qya, Qya1, Qya2, Qia, Qia1, Qia2, Qoa) Eolian deposits (Qe) Rock fall deposits (Qrf) Colluvium and colluvial-fan deposits (Qc) Landslide deposits (Qls) Spring deposits (Qs)	Extensive erosion, downcutting, and aggradation (elevation increase due to sediment infill) related to integration of the Rio Grande.
Pliocene (PL)	5.33 million to 2.58 million years ago	Fingers formation (Pliocene–Pleistocene) (QTa) Estufa Canyon formation (Pliocene–Pleistocene) (QTa)	Basin-and-range faulting within BIBE occurred from about 25 million to 2 million years ago. Miocene and Pliocene units largely represent basin-fill deposits and mass-movement deposits.
Miocene (MI)	23.03 million to 5.33 million years ago	<u><i>Delaho Formation</i></u> (Ta): • Smoky Creek Member (Ta) Banta Shut-in formation (Ta) Gravity slide blocks (Miocene?) (Tgs)	Basin-and-range faulting within BIBE occurred from about 25 million to 2 million years ago. Miocene and Pliocene units largely represent basin-fill deposits and mass-movement deposits.
Oligocene (OL)	33.9 million to 23.03 million years ago	Volcanic rocks, undivided (Tv) Intrusive complex at Rattlesnake Mountain (Tirc) Basaltic flow (Tfb) Burro Mesa Formation: • Rhyolite member (Tbr) • Wasp Spring member (Tbw) • Intrusive rocks, undivided (Tbi) Trachytic lava, undivided (Tt) Sierra Quemada related rocks: • Sierra Quemada ring dike (Tqd) • Intrusive rocks, undivided (Tqi) • Vent breccia (Tqv)	The Pine Canyon caldera complex and other laccolith complexes developed circa 32 million years ago. Evidence of basin-and-range extensional faulting dates back approximately 25 million years ago.

Geologic Time Unit	Age	Geologic Units (GSRI map symbol)	Geologic Events
Oligocene (OL), cont.	33.9 million to 23.03 million years ago	Dominguez Mountain related rocks: • Mafic lava flows (Tdm) • Dike swarm (Tdd) • Intrusive rocks, undivided (Tdi) <u>South Rim Formation:</u> • <u>Emory Peak rhyolite member</u> (Tse) • Boot Rock member (Tsb) • Pine Canyon rhyolite member (Tsp) • Intrusive rocks, undivided (Tsi) Intrusive igneous rocks related to the Grapevine Hills (Tigh), McKinney Hills (Timh), and Rosillos Mountains (Tirm) Intrusive rocks, undivided (Ti) Rhyolitic and other felsic intrusive rocks, undivided (Eocene–Oligocene) (Tir) Andesitic and other intermediate intrusive rocks, undivided (Eocene–Oligocene) (Tia) Basaltic and other mafic intrusive rocks, undivided (Eocene–Oligocene) (Tib) Chisos Formation: • Younger part, undivided (Eocene–Oligocene) (Tcy) • <u>Tule Mountain Trachyandesite Member</u> (Tctm) • <u>Bee Mountain Basalt Member</u> (Tcbm) • <u>Mule Ear Spring Tuff Member</u> (Tcme)	The Pine Canyon caldera complex and other laccolith complexes developed circa 32 million years ago. Evidence of basin-and-range extensional faulting dates back approximately 25 million years ago.
Eocene (E)	56.0 million to 33.9 million years ago	Chisos Formation: • Lava flows, undifferentiated (Tcl) • <u>Ash Spring Basalt Member</u> (Tcas) • <u>Alamo Creek Basalt Member</u> (Tcac) • Older part, undivided (Tco) • Sandstone, tuff, and rhyolite unit (Tcstr) • Siltstone unit (Tcks) • Rhyolite tuff unit (Tcrt) Christmas Mountains related volcanic rocks (Tx): <u>Canoe Formation</u> (Tc) • <u>Big Yellow Sandstone Member</u> (Tc) Hannold Hill Formation (Thh): • Exhibit Sandstone Member (Thh)	Major volcanism in BIBE began about 47 million years ago and ended about 29 million years ago.

Geologic Time Unit	Age	Geologic Units (GSRI map symbol)	Geologic Events
Paleocene (EP)	66.0 million to 56.0 million years ago	<u>Black Peaks Formation</u> (Paleocene to Upper Cretaceous) (TKbp)	Fluvial and floodplain environments.
Cretaceous (K)	145 million to 66 million years ago	<u>Javelina Formation</u> (Kj) <u>Aguja Formation</u> (Ka): • <u>Alto Shale Member</u> (Ka) • <u>Terlingua Creek Sandstone Member</u> (Ka) • <u>Rattlesnake Mountain Sandstone Member</u> (Ka) • <u>Abajo Shale Member</u> (Ka) • <u>La Basa Sandstone Member</u> (Ka) <u>Pen Formation</u> (Kp): • <u>McKinney Springs Tongue</u> (Kp) <u>Boquillas Formation</u> (Kb): • <u>San Vicente Member</u> (Kbs) • <u>Ernst Member</u> (Kbe) Buda Limestone (Kbd, Kbu) Del Rio Clay (Kbd, Kdr) <u>Santa Elena Limestone</u> (Kse) <u>Sue Peaks Formation</u> (Ksp) <u>Del Carmen Limestone</u> (Kdc) <u>Telephone Canyon Formation</u> and Maxon Sandstone, undivided (Ktm) Glen Rose Limestone (Kgr)	A notable uniformity separates Cretaceous strata from underlying Paleozoic rocks and records a major period of erosion. These Cretaceous rocks record shallow marine carbonate shelf environments that experienced cyclic influxes of terrigenous material from uplifted regions in the Marathon region north of BIBE. By the end of the Cretaceous Period, a shift to mostly fluvial floodplain environments occurred in tandem with the onset of the Laramide orogeny (about 70 million years ago).
Pennsylvanian (PN) Mississippian (M) Devonian (D) Silurian (S) Ordovician (O)	485.4 million to 298.9 million years ago	Tesusus Formation (Lower Pennsylvanian and Upper Mississippian) (PNMt) Paleozoic rocks, undivided (Ordovician–Pennsylvanian) (PZu) Caballos Novaculite (Mississippian to Silurian) (MOu) Maravillas Formation (Upper to Middle Ordovician) (MOu)	The Maravillas Formation and Caballos Novaculite were deposited in marine deep-water environments. The Tesnus Formation is considered a synorogenic flysch (rocks formed during collision) deposited in front of the advancing Marathon orogenic belt. During the Marathon orogeny (about 330 million to 285 million years ago), deep oceanic rocks were thrust northwestward during the convergence of the North and South American plates.

Igneous Activity

A major component of BIBE's landscape and geologic history is related to middle Tertiary (Eocene–Oligocene Epochs) volcanism that began about 47 million years ago and ended approximately 29 million years ago (Turner et al. 2011). The Big Bend region was part of a large volcanic field known as the Trans-Pecos volcanic field that includes parts of southwest Texas and northern Mexico. Volcanism and plutonism were driven by a tectonic shift from Laramide compression to basin-and-range extension; these opposing stress regimes influenced magma generation, source, and composition over time. Volcanic rocks (e.g., lava flows, tuffs, breccias, debris flows, volcanic blocks/bombs) are widely mapped throughout the Chisos Mountains and the Delaho bolson and comprise several formations that include (in chronological order) the Eocene Canoe Formation (**Tc**), Eocene–Oligocene Chisos Formation (**Tcy**, **Tctm**, **Tcbm**, **Tcme**, **Tcl**, **Tcas**, **Tcac**, **Tco**, **Tcstr**, **Tcks**, **Tcrt**), Oligocene South Rim Formation (**Tse**, **Tsb**, **Tsp**, **Tsr**, **Tsd**, **Tsi**), and Burro

Mesa Formation (**Tbr, Tbw, Tbi**). Thick sequences of volcanic rock were extruded from a complex system of volcanic vents and lava domes that include the Pine Canyon caldera. Around 32 million years ago, the eruption of the Pine Canyon caldera produced the volcanic strata of the South Rim Formation that are widely preserved in the high Chisos Mountains. Volcanic deposition is largely responsible for preserving the diverse, abundant paleontological resources found throughout the national park.

Accompanying volcanic activity was magmatism, which produced several plutonic bodies, including intrusive complexes (crystallized magmas of various compositions that are the result of multiple, coeval emplacement events), laccoliths (a type of igneous intrusion that causes overlying rock layers to bulge), domes (circular, mound-shaped protrusions), dikes (vertical or near vertical intrusions of igneous rock), and sills (flat, sheet-like intrusions of igneous rock). These intrusive rocks were derived from multiple magma sources and represent a diverse suite of rocks ranging from felsic to mafic compositions. Features associated with Big Bend magmatism include the Pine Canyon caldera, South Rim (**Tsb**), Sierra Quemada (**Tgd, Tgi, Tgv**), Dominguez Mountain (**Tdm, Tdd, Tdi**), Ward Mountain (**Tsi**), Pulliam Peak (**Tsi**), Rosillos Mountains (**Tirm**), McKinney Hills (**Timh**), Grapevine Hills (**Tigh**), and Rattlesnake Mountain (**Tirc**). Intrusive sills, dikes, and other tabular bodies (**Tia, Tib, Tir**) are mapped surrounding the Rosillos Mountains, Dagger Flat, Bone Spring, Glenn Spring, Government Spring, Mariscal Mountain, Cow Heaven Mountain, Chilicotal Mountain, Talley Mountain, Slickrock Mountain, Paint Gap Hills, and Croton Peak. Throughout BIBE, the development of major intrusive bodies such as laccoliths has penetrated, uplifted, and folded older Cretaceous and Tertiary rocks (see “Faults and Folds”).

Structural Geology

Faults

Although the oldest strata exposed in BIBE are Paleozoic rocks, its geologic history spans over a billion years and includes rifting events dating back to the Proterozoic Eon. Older basement faults such as the Texas Lineament extend across the national park into Mexico and may have formed from multiple rifting events that occurred along the southern continental margin of North America during the Mesoproterozoic Era (about 1.5 billion to 1.0 billion years ago) and Neoproterozoic Era (800 million to 550 million years ago; Figure 7; Turner et al. 2011). These ancient, buried fault structures are zones of weakness that likely influenced the long-term geological evolution of BIBE’s landscape and are speculated to have been re-activated during the late Paleozoic Marathon orogeny, Cretaceous–early Tertiary Laramide orogeny, and late Tertiary basin-and-range faulting.



Figure 7. Map of basement faults. Map depicts basement faults related to Proterozoic rifting between the North and South American plates. Solid black lines are Neoproterozoic transform faults; gray, double-banded lines represent rift zones; and solid red lines are fault structures associated with the Mesoproterozoic Texas Lineament. Figure 9 from Turner et al. (2011).

The Big Bend region is structurally complex, containing numerous northwest–southeast-oriented faults that include the Terlingua, Burro Mesa, Chalk Draw, and Dugout Wells faults (see Figures 6 and 8). These high-angle normal faults are major structural features associated with basin-and-range extension and are responsible for the development and infilling of local depositional basins such as the Delaho and Estufa bolsons. Normal faults are also responsible for the national park’s hydrothermal resources, as water heated at depth travels along the faults to the surface, where it emerges from springs along the Rio Grande corridor (see “Hydrological and Hydrothermal Resources”). In addition to extensional normal faults, the Santiago thrust near Persimmon Gap is a major compressional Laramide fault that exposes the oldest rocks in BIBE.

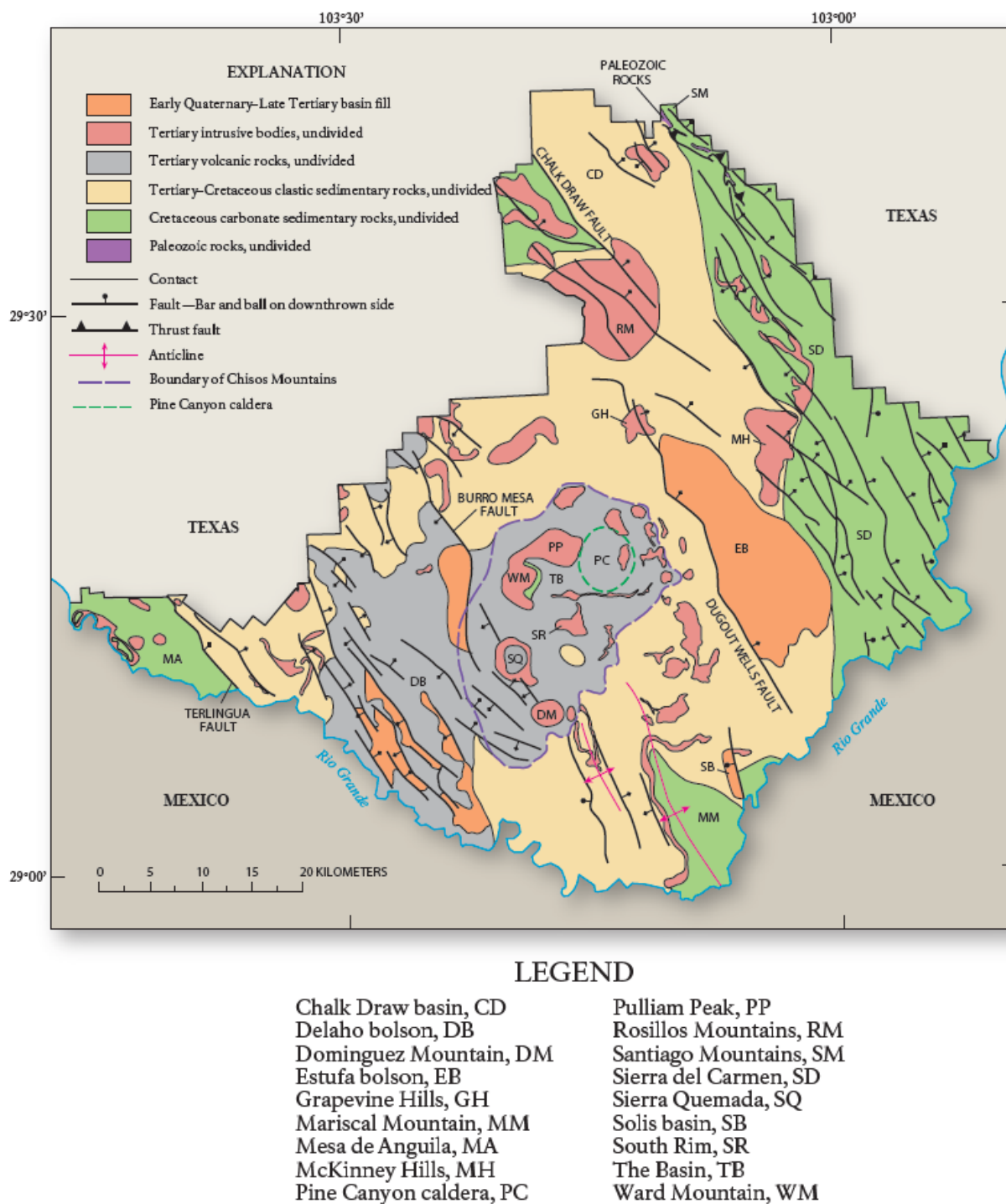


Figure 8. Generalized geologic map. The map includes geology, major fault structures, and geographic features in BIBE. Figure 2 from Turner et al. (2011).

Folds

Major folds within the national park include several northwest-trending Laramide structures such as the Mesa de Anguila monocline, Terlingua monocline, Cow Heaven anticline, Mariscal Mountain anticline, and Sierra del Carmen–Santiago Mountains monocline (see Figure 5). Overturned anticlinal exposures occur along the Santiago thrust near Persimmon Gap. Several additional folds occur in Cretaceous strata east of

Terlingua Creek, near Slickrock Mountain, and southeast of McKinney Hills. Although these folds are likely related to Laramide deformation, their proximity to Oligocene intrusions makes it difficult to determine their relationship to magmatic uplift. In the Chisos Mountains, folded volcanic and intrusive rocks are attributed to Oligocene magmatism and include the Hayes Ridge anticline (formed due to the collapse of the Pine Creek caldera) as well as local folds formed by domes, plutons, and other intrusions.

Extensional Basins

Late Tertiary regional extension related to the development of the Basin-and-Range province resulted in several high-angle normal faults that contributed to the development of local depositional basins such as the Delaho and Estufa bolsons on the flanks of the Chisos Mountains (see Figure 6). Through geologic time, the headwall or “sunken” blocks along these faults have been infilled by a thick sequence of Miocene to Pleistocene sediments. Located west of the Chisos Mountains, the Delaho bolson contains dissected alluvium and alluvial fan deposits of the Delaho Formation (**Ta**) and informal Fingers formation (**QTa**). The bolson is transected by several steep ($>70^\circ$) northwest–southeast-trending faults that record up to 500 m (1,650 ft) of offset and is bounded to the northeast by the Burro Mesa fault and to the southwest by the Terlingua fault (Turner et al. 2011). On the opposite side of the Chisos Mountains, the Estufa bolson is an elongated basin that spans 25 km (15 mi) in length and 10 km (6 mi) in width. To the west, the bolson is bounded by the Dugout Wells fault. Basin-fill deposits consist of alluvium and alluvial fan sediments of the informal Banta Shut-in (**Ta**) and Estufa Canyon (**QTa**) formations. Sequences of basin fill within the Estufa bolson are punctuated by fewer normal faults and are generally less dissected and more intact compared to the Delaho bolson.

Along with the earlier deposition of the various Paleogene volcanic rocks, the development and subsequent infilling of the national park’s extensional basins have helped preserve much of the underlying fossil-bearing strata from erosion (Wick and Corrick 2015).

Unconformities

Layers of rock are referred to as “conformable,” where they have been deposited essentially without interruption. Although rock exposures may exhibit conformable beds that represent significant spans of geologic time, no place on Earth contains a full set of conformable strata. Breaks in conformable strata are called “unconformities.” Each unconformity represents a period of “missing” geologic time when deposition ceased or where erosion has removed an interval of the rock record.

The following unconformities occur in BIBE:

- (1) Exposures in the Santiago Mountains record a major unconformity between the Lower Cretaceous Glen Rose Limestone (**Kgr**) and the underlying Paleozoic rocks of the Mississippian–Pennsylvanian Tesnus Formation (**PNMt**).
- (2) An angular unconformity exists between the Oligocene South Rim Formation (**Tsp**, **Tsb**, **Tsi**) and the underlying Eocene–Oligocene Chisos Formation (**Tcy**, **Tcbm**) around the perimeter of the Pine Canyon caldera.
- (3) In the Chisos Mountains, the Eocene–Oligocene Chisos Formation contains an internal unconformity separating younger tuffaceous sedimentary rocks from older tuffaceous sedimentary units that predate the Alamo Creek Basalt Member (**Tcac**). Additionally, the Chisos Formation unconformably overlies the Upper Cretaceous Aguja (**Ka**) and Javelina (**Kj**) Formations in the Chisos Mountains and the Upper Cretaceous–Paleocene Black Peaks Formation (**TKbp**) on the eastern flank of the Chisos Mountains. In many places throughout BIBE, the Alamo Creek Basalt Member unconformably overlies the Black Peaks Formation.

- (4) The Eocene Canoe Formation (Big Yellow Sandstone Member; **Tc**) is unconformable with the underlying Eocene Hannold Hill Formation (**Thh**) in the Tornillo Flat area. Additionally, the Canoe Formation unconformably overlaps folds and faults in the Black Peaks, Javelina, and Aguja Formations.
- (5) The Upper Cretaceous Buda Limestone (**Kbd, Kbu**) is unconformably overlain by the Upper Cretaceous Boquillas Formation (**Kb, Kbs, Kbe**).
- (6) The Mississippian–Pennsylvanian Tesnus Formation (**PNMt**) is unconformable with the underlying Silurian–Mississippian Caballos Novaculite (**MOu**).
- (7) The Silurian–Mississippian Caballos Novaculite is unconformable with the underlying Ordovician Maravillas Formation (**MOu**).
- (8) Basin-fill deposits of the informally named Miocene Banta Shut-in formation (**Ta**) are unconformably overlain by alluvial fan deposits of the informally named Pliocene–Pleistocene Estufa Canyon formation (**QTa**).

Fluvial Systems

Major landscape features of BIBE include the Rio Grande and its tributaries such as Alamo, Blue, Fresno, Heath, Smoky, Terlingua, and Tornillo Creeks. Due to its scenic, geologic, recreational, and cultural values, a 307 km (191 mi) segment of the Rio Grande was designated a Wild and Scenic River in 1978, of which 111 km (69 mi) exist along the national park’s southeastern boundary downstream from Mariscal Canyon. With its headwaters in the Rocky Mountains, the Rio Grande flows over 3,000 km (1,900 mi) from Colorado to the Gulf of Mexico and is supported by one of the largest drainage areas in the United States. In southwest Texas, the waters of the Rio Grande are largely (80–90%) sourced from the Rios Conchos (National Park Service 2018). However, a portion of the 300 or more natural springs and seeps found throughout the national park also discharge into the river and contribute to the overall health of the fluvial system (Nadeau et al. 2014; Atkinson 2016; McIntyre et al. 2018). The modern landscape of BIBE has been extensively modified by erosion, downcutting, and aggradation related to the Rio Grande system since the Pleistocene Epoch around 2 million years ago (Turner et al. 2011). Natural features such as massive canyons (e.g., Santa Elena, Mariscal, Boquillas, San Vicente, and Hot Springs Canyons) and pour-offs (e.g., the Window, and Burro Mesa Pour-off) have been incised by the persistent erosive power of the river and its tributaries. Quaternary deposits record the fluvial evolution of the region and consist of active tributary and river deposits (**Qaw**), axial river deposits (**Qyw1, Qyw2, Qiw, Qiw1, Qiw2, Qiw3, Qow**), and alluvial deposits (**Qya, Qya1, Qya2, Qia, Qia1, Qia2, Qoa**).

In the Chihuahuan Desert, the Rio Grande system provides a valuable source of water and supports extensive ecologically intact aquatic and riparian habitats (National Park Service 2018). The flow of the river dramatically fluctuates in response to seasonal changes in temperature and precipitation, in addition to anthropogenic diversions. During the summer and fall, peak monsoonal precipitation causes recurrent seasonal flooding and flash flooding events (see “Flooding and Flash Flooding”). As a result of human activity, the Rio Grande is no longer a free-flowing river system. Over the last several decades, anthropogenic diversions (e.g., dam construction and increased water usage) and infestations of human-introduced non-native species such as *Arundo donax* (giant cane or carrizo) and *Tamarix* (tamarisk or salt cedar) have negatively impacted the hydrological conditions of the Rio Grande. Human alterations have diminished the river’s mean flow rate to the extent that certain segments experience periods of intermittent flow. These modifications in flow have reduced sediment transport, increased water pollution, and modified the morphology of the river from a braided to a single-channel system (Nadeau et al. 2014). According to climate change projections, any increases in mean annual temperature, storm frequency, and droughts could

further impact water quality, reduce average flows, and increase episodic runoff and/or flooding along the Rio Grande (National Park Service 2016).

Hydrological and Hydrothermal Systems

Water is a vital resource in the national park and is supplied through a variety of sources such as springs, seeps, riparian wetlands, tinajas (bedrock depressions that hold water), groundwater aquifers, and the Rio Grande system (see “Fluvial Features and Resources”). Seasonal changes in precipitation and temperature govern the recharge and discharge of these hydrological resources, many of which belong to a network and flow into the Rio Grande. According to the GSRI GIS data (source map by Turner et al. 2011), only a few spring deposits (**Qs**) occur within BIBE, the largest of which consists of roughly 5 m (16 ft) of carbonate and silt found near Grapevine Spring.

Springs and Seeps

More than 300 springs and seeps are in the Big Bend area, a majority (75%) of which are seasonal and fed by small, local aquifers (Nadeau et al. 2014; McIntyre et al. 2018; National Park Service 2018). Water availability is a critical management concern within the national park, and hydrological resources such as springs and seeps are threatened by groundwater withdrawals, climate change, recreational use, invasive species, and aging park infrastructure (Nadeau et al. 2014; National Park Service 2016, 2018). Drinking water supplies within BIBE are all groundwater-dependent, meaning the water supply system is stressed during dry years compared to wet years (National Park Service 2018).

The national park contains a limited number (approximately 12) of hydrothermal springs concentrated along the banks of the Rio Grande (Ozaki 2003). Hydrothermal resources, such as the Langford Hot Springs Complex and the Lower Canyons Thermal Spring Complex, are considered important areas for protection and possess significant ecological, historical, and recreational values. At the Rio Grande Village, hydrothermal springs are not only a source of domestic water use but also provide critical habitat for the federally endangered Big Bend gambusia (*Gambusia gaigei*). The gambusia is a species of fish that is sensitive to fluctuations in water quality, quantity, and temperature; the only remaining wild population of gambusia exists in a protected pond within BIBE.

Like other springs or seeps in the park, hydrothermal springs flow into the Rio Grande and contribute to the overall discharge and water quality of the river. Unlike smaller springs or seeps, hydrothermal springs are supplied by large regional aquifers that maintain consistent discharge and are less susceptible to seasonal fluctuations in precipitation and temperature (Nadeau et al. 2014). Water sourced from these regional aquifers is generally along faults at greater depth, where the geothermal gradient heats the water to nearly 40.1°C (104°F; Maxwell 1968; Shanks et al. 2008).

The Hot Springs district preserves a rich history of human occupation that includes Indigenous tribes and early Spanish, Mexican, and American settlers who utilized the hot springs for their reputed healing powers. Visitors who opt to explore Langford Hot Springs can observe petroglyphs in the cliffs along the trail and sit within the historic foundations of J. O. Langford’s early 20th-century bathhouse. Additional hydrothermal resources within the park include skarn deposits (hydrothermally metamorphosed carbonate rocks) near Dagger Flats (Morgan and Shanks 2008), in addition to caves of possible hydrothermal origin (see “Caves and Karst Resources”).

Groundwater Aquifers

Important aquifers within BIBE occur in three main geologic units: Cretaceous sedimentary rocks, Tertiary volcanic rocks, and Quaternary alluvium deposits (Atkinson 2016; Raymond et al. 2022). Cretaceous strata such as the Santa Elena Limestone (**Kse**) contain some of the most reliable aquifers, supply a large fraction

of the national park's well water, and are major groundwater contributors to the Rio Grande and adjacent springs or seeps. Aquifers found in Tertiary volcanic rocks are concentrated in rubble deposits located below lava flow layers or in fractures and crevices formed in the upper portions of lava flows as they quickly cooled (Raymond et al. 2022).

Groundwater serves as a vital natural resource and a major source of drinking water within BIBE. Groundwater wells located along the Rio Grande floodplain are hydrologically connected to the river system, meaning that various contaminants (e.g., pesticides, bacteria, industrial chemicals) found in the river are also present in the domestic water supply. The degradation of water quality at Castolon is a potential health and safety hazard due to high amounts of dissolved solids (high sulfate quantities). Additional groundwater quality issues stem from the landfill near Grapevine Hills Road. After heavy rain activity, fissures form on the landfill surface, which may pose a potential source of groundwater contamination (Ozaki 2003).

Wetlands

Wetlands within BIBE represent a critical component of the Chihuahuan Desert ecosystem that provide habitat, promote biodiversity, and serve as buffers against erosion. Two distinct types of wetlands are present that are associated with springs and seeps or are located along the Rio Grande corridor. Both wetland types cover a combined area of ~650 ha (1,606 ac) and are vulnerable to changes in groundwater availability, surface water discharge, and the introduction of invasive species (Nadeau et al. 2014). Alterations to the natural flow and flood regime of the Rio Grande have resulted in channel narrowing and water quality degradation, which have negatively impacted riparian wetlands.

Cave and Karst

The national park contains several cave features that record both karst (dissolution) and pseudokarst (non-dissolution) processes. Karst landscapes form through the natural dissolution of soluble rocks, commonly carbonates such as limestone or dolostone. In contrast, pseudokarst topography resembles true karst but is formed through non-dissolution mechanisms such as jointing (the development of cracks or fractures that lack displacement) and lava emplacement (lava tubes). According to Atkinson (2016), BIBE contains 75 known or documented caves, six rumored or undocumented caves, 34 documented cave-like rockshelters, and six sinkholes and karst cavities. Of the 75 known or documented caves, approximately 68 (91%) formed through the dissolution of carbonate rock. Many additional cave and karst features are likely to exist but have not been identified or recorded due to the national park's remote, rugged desert setting. Caves throughout BIBE are generally small and inaccessible.

The Cretaceous sedimentary strata in BIBE form an extensive sequence of rocks more than 1,400 m (4,600 ft) thick and include several carbonate units, such as the Santa Elena Formation (**Kse**) and Buda Limestone (**Kbd, Kbu**), that are known to host solutional caves and shelters. Located in the Mesa de Anguila, Mariscal Mountains, and Sierra del Carmen regions of the national park, these caves are believed to be of hydrothermal origin and contain abundant calcite spar coatings and multi-level, fissure-like passages. In one cave, the walls are covered with banded, multi-colored ore minerals that were apparently mined or disturbed. The speleogenesis (cave origin and development) of these solutional caves has had limited study and remains a topic of interest.

Pseudokarst caves and cavities have been documented in sediments of the Aguja Formation (**Ka**) in addition to volcanic flows and volcanoclastic deposits of the Chisos Formation (**Tcy, Tctm, Tcbm, Tcme, Tcl, Tcas, Teac, Tco, Tcstr, Tcks, Tert**; Atkinson 2016). These pseudokarst features formed through two types of processes—tectonic fracturing and suffusion (piping)—which are caused by the mechanical erosion of sandstone and mudstone rocks. Although volcanism is part of Big Bend's geologic story, no lava tubes have been reported from within BIBE. It should be noted that pseudokarst features developed through suffusion are poorly understood and may represent a significant karst type.

Several legends exist about the national park's caves that include outlaws, cattle rustlers, and Indigenous ghosts (Maxwell 1968). Cultural materials are present in 23 of the documented caves and rock shelters, with most consisting of projectile points, lithic scatter, mortar holes, tool marks, smoke-stained ceilings, stone tools, and pictographs or petroglyphs (Maxwell 1968; Atkinson 2016). Although archeological and cultural resources are well documented within the national park, the paleontological resources of Big Bend's cave and karst features are relatively unknown. The study of invertebrate fossils within the caves of BIBE is essentially nonexistent (Atkinson 2016). Three caves are considered historical and date back to early 20th-century mineral and bat guano mining. Today, caves at BIBE serve as an important source of shelter for the park's numerous bats, including the endangered Mexican Long-nosed Bat (*Leptonycteris nivalis*).

Soils, Crusts, and Desert Pavements

The distribution of various soil types, crusts, and desert pavements influences the vegetation, ecosystems, and erosional processes throughout BIBE. Soil quality throughout the national park is generally influenced by elevation, as higher-quality soils occur at higher altitudes where there is more available moisture, precipitation, and cooler temperatures. Desert pavements cover the flat plains and develop when wind scours away small particles (e.g., sand, silt, clay), leaving behind a layer of pebbles and rocks armoring the ground surface. Physical and microbiotic crusts present throughout BIBE represent unique, fragile resources that are easily impacted or created by human actions. For example, historic overgrazing practices throughout the Big Bend region removed grass and other vegetative cover, which facilitated the development of physical crusts on a large scale. The creation of physical crusts reduced water infiltration into the soil, increased overland flow, concentrated runoff, and helped generate erosional gulley systems (see "Disturbed Lands"). Microbial crusts are biological soils created by microbial communities (fungi, cyanobacteria, and lichens) that bind organic matter together within the upper centimeters of the soil surface. Although these microbial crusts are believed to contribute organic matter that benefits soil health, their extent, distribution, and colonization rate are currently unknown. Additionally, microbiotic soils may be susceptible to eolian processes (e.g., dust storms), which deposit sediment particles that smother microbial communities (Ozaki 2003).

Current issues of concern regarding BIBE's soils include soil texture, soil structure, organic matter content, infiltration, and soil erosion. Soil erosion is a management concern that is driven by multiple processes such as cattle grazing (including both historic ranching and modern livestock trespassing), wind erosion, and gully development. The extension of gully systems continues to erode soils and decrease the distribution of native grasslands. Overgrazing has negatively impacted areas like Tornillo Flat, and soil restoration efforts are problematic because of soil loss (see "Disturbed Lands"; Ozaki 2003). Areas of NPS soil restoration that took place in the 1950s and 1960s are now eroding (National Park Service 2018).

Eolian Features and Processes

The term "eolian" refers to windblown erosion, transportation, and deposition of sediments. According to the GSRI GIS data (source map Turner et al. 2011), the youngest surficial deposits are Holocene eolian sands (**Qe**), which form localized nabkhas (dunes that form around vegetation) along the southern boundary of BIBE. These deposits are limited in extent within the national park and are mapped along Terlingua Creek near the Santa Elena Canyon overlook; northeast of the Dorgan House trail; along the Rio Grande immediately south of the Dominguez campsite; and at Boquillas Canyon. Eolian deposits have also been described along the valley floors of the Tornillo Flat region (Berry and Williams 2008). Just outside BIBE, a large dune field exists south of the Rio Grande in the village of Boquillas Del Carmen. These dunes provide a source of mobile sand, and the village is known as a wind tunnel (Ozaki 2003). Additionally, a large sand slide (a debris flow comprised predominantly of sand-sized grains) exists near the mouth of Boquillas Canyon on the Mexican side of the Rio Grande.

Eolian processes such as dust storms occur throughout the national park region and represent a management concern as they are known to mobilize and remove large quantities of surficial material, including soil. The frequency and magnitude of these storms are affected by human actions, including overgrazing, mining, farming, and other activities that remove vegetation (see “Disturbed Lands”). Since the mid-1980s, grassland restoration activities in regions such as Tornillo Flat have helped reduce the occurrence of dust storm activity (Ozaki 2003).

Paleontology

Paleontological (fossil) resources have been known in the Big Bend region since the late 19th century, and BIBE has had a continuous record of investigation since the 1930s. Fossils are preserved in many of the geologic units of the national park and include significant Cretaceous and lower Tertiary vertebrate and plant localities (Table 2). To date, BIBE’s paleontological record includes more than 1,200 species and represents the greatest collection of Cretaceous dinosaur body fossils in the National Park System (Tweet and Santucci 2018; Santucci et al. 2018). Several noteworthy discoveries include the largest known crocodilian and the largest known flying vertebrate in Earth history (see “Dinosaurs, Mammals, and the K-Pg Boundary”). The *Paleontological Inventory of Big Bend National Park, Texas* by Wick and Corrick (2015) is an outstanding, detailed resource regarding the national park’s paleontological history, research, and collections.

Table 2. Paleontological resources by geologic unit.

The following table shows the paleontological resources associated with the geologic units within BIBE. Information for the table was sourced from Santucci et al. (2007), Turner et al. (2011), and Wick and Corrick (2015).

Geologic Age	Geologic Unit Name	Fossil Resources
Quaternary	Basin-fill and alluvium	Mammoth teeth
Pliocene–Pleistocene	Fingers formation	None documented to date
Pliocene–Pleistocene	Esufa Canyon formation	Vertebrate fossils including mammals (horse, rodents, ungulates) and turtles; notable mastodon bones
Miocene	Delaho Formation	Vertebrate fossils including mammals, tortoises, and lizards
Miocene	Banta Shut-in formation	Vertebrate fossils including mammals, tortoises, lizards, snakes, and toads
Oligocene	Burro Mesa Formation	None documented to date
Oligocene	South Rim Formation	None documented to date
Eocene–Oligocene	Chisos Formation	Vertebrate fossils including mammals (ancestral camel, rabbit, deer, sheep-like grazers) and turtles <i>Note:</i> Pleistocene vertebrate fossils (California condor) found in caves of the Chisos Formation
Eocene	Canoe Formation	Mammals
Eocene	Hannold Hill Formation	Mammals (ancestral horse) and fish
Cretaceous–Paleocene	Black Peaks Formation	Vertebrate fossils including dinosaurs (sauropod), mammals, and fish. Invertebrate fossils including bivalves and gastropods. Plant fossils including petrified wood.
Cretaceous	Javelina Formation	Vertebrate fossils including dinosaurs (ceratopsian, sauropods, theropods such as <i>Tyrannosaurus</i> , and a notable pterosaur assemblage including the largest known flying creature, <i>Quetzalcoatlus northropi</i>). Insect fossils. Plant fossils including petrified wood.

Geologic Age	Geologic Unit Name	Fossil Resources
Cretaceous	Aguja Formation	Terrestrial deposits contain vertebrate fossils including dinosaurs (ceratopsians), turtles, sharks, fish, crocodiles (including the "super-croc" <i>Deinosuchus riograndensis</i>), mammals, and plant fossils including petrified wood, leaves, stems, seeds, fruits, and coal. Marine units contain ammonites, oysters, and fish scales and bones
Cretaceous	Pen Formation	Invertebrate fossils including ammonites, bivalves, and gastropods. Vertebrate fossils including mosasaurs (marine lizards), sharks, fish, and turtles. Trace fossils.
Cretaceous	Boquillas Formation	Invertebrate fossils including ammonites, bivalves, and cephalopods. Microfossils including foraminifera. Vertebrate fossils including mosasaurs, sharks, and fish.
Cretaceous	Buda Limestone	Invertebrate fossils including bivalves, cephalopods, and gastropods
Cretaceous	Del Rio Clay	Invertebrate fossils including bivalves and echinoids. Microfossils including foraminifera.
Cretaceous	Santa Elena Limestone	Invertebrate fossils including rudistids and gastropods. Microfossils including foraminifera.
Cretaceous	Sue Peaks Formation	Invertebrate fossils including gastropods, echinoids, and ammonites
Cretaceous	Del Carmen Limestone	Invertebrate fossils including rudistids, gastropods, and echinoids. Microfossils including foraminifera.
Cretaceous	Telephone Canyon Formation	Invertebrate fossils including echinoids, bivalves, and gastropods
Cretaceous	Maxon Sandstone	None documented to date
Cretaceous	Glen Rose Limestone	Invertebrate fossils including bivalves, gastropods, and echinoids
Mississippian–Pennsylvanian	Tesnus Formation	None documented to date
Mississippian–Silurian	Caballos Novaculite	None documented to date
Ordovician	Maravillas Limestone	Invertebrate fossils including brachiopods, crinoids, bryozoans, and conodonts

Baseline GSRI Products

Geology

The digital geologic map for BIBB is available on the NPS DataStore, accessed through the Integrated Resource Management Applications (IRMA) portal (see <https://irma.nps.gov/DataStore/Reference/Profile/2175534>) and is adapted from the USGS Scientific Investigations Map by Turner et al. (2011). For many decades, the geologic map and report of Maxwell et al. (1967) provided the most comprehensive account of the stratigraphic, volcanic, geomorphological, paleontological, and structural features of BIBB. The latest map and report by Turner et al. (2011) represent a synthesis of new maps, studies, and geologic age dates that provide greater detail than the original map of Maxwell et al. (1967). Additional GSRI documents include the NPS Geoindicators Scoping Report (Ozaki 2003).

Source map:

Turner, K. J., M. E. Berry, W. R. Page, T. M. Lehman, R. G. Bohannon, R. B. Scott, D. P. Miggins, J. R. Budahn, R. W. Cooper, B. J. Drenth, E. D. Anderson, and V. S. Williams. 2011. Geologic map of Big Bend National Park, Texas. US Geological Survey, Reston, Virginia. Scientific Investigations Map 3142. Scale 1:75,000. <https://pubs.usgs.gov/sim/3142/> (accessed 26 June 2024).

Geoindicators Scoping Report:

Ozaki, V. 2003. Geoindicators scoping report for Big Bend National Park. National Park Service Geologic Resources Division, Denver, Colorado. <https://irma.nps.gov/DataStore/Reference/Profile/2302894>.

Soils

Soil mapping by the NPS Soil Resources Inventory (SRI) was updated for BIBB in 2013 and is available through IRMA, in addition to a detailed soil survey report published in 2011 by the US Department of Agriculture, Natural Resources Conservation Service (NRCS), and the SRI (United States Department of Agriculture, Natural Resources Conservation Service and United States Department of Interior, National Park Service 2011). Additional soil data and maps for Brewster County, Texas, are provided by the National Cooperative Soil Survey Geographic Database (SSURGO; <https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx>).

The national park boundary currently extends over two NRCS soil survey areas (both completed):

- TX621 Big Bend National Park, Texas
- TX622 Brewster County, Texas (Main Part)

Geologic Resource Management Issues and Inventory Needs

Geologic Hazards

Park resources are not only visitor attractions but may also be potentially hazardous. The Big Bend landscape presents a variety of geologic hazards, or “geohazards”—naturally occurring, dynamic geologic processes that have the potential to cause damage, loss of property, and/or injury and loss of life (Table 3).

Table 3. Geologic hazards checklist.

This summary table is a synthesis of existing GSRI-compiled map data and information, as well as published US Geological Survey and other government agency information. It is suitable for use at park-scale discussions and assessments. It is not a substitute for site-specific investigations or NEPA analysis. Ground-disturbing activities should neither be approved nor denied based on the information here. This table is modeled after the Natural Hazard Checklist (see National Park Service 2015 and Jarvis 2015). It is meant to provide general information to identify the full range of natural hazard-based risks for the national park.

Hazard	Examples of Risk or Secondary Hazard	Best Professional Judgment	Sources of Geohazard Information
Earthquake	Falling objects Collapsing structures Inoperability of major building systems (e.g., power, sewer, water) Trigger to other hazards (e.g., landslides, rockfalls) Human injury or casualty	Potential Hazard (Low)	US Department of Interior (DOI) Strategic Hazard Identification and Risk Assessment (SHIRA) Risk Mapper Report United State Geological Survey (USGS) Earthquake Hazard Probability Map (Petersen et al. 2023)
Slope movements (also called “mass wasting”)	Rockfalls, landslides, or flows Partial constriction of the Rio Grande system Damage or destruction of park infrastructure Damage to or loss of natural or cultural resource sites or features Human injury or casualty	Known Hazard (Susceptible to landslides, rockfalls)	DOI SHIRA Risk Mapper Report GSRI GIS hazard layers or slope movement deposits (e.g., “landslide deposits,” “rockfall deposits,” “gravity slide blocks,” “colluvium and colluvial-fan deposits”) Maxwell et al. (1967) Maxwell (1968) Turner et al. (2011)
Permafrost	Not applicable	Not applicable	Not applicable
Cave/karst	Sinkholes Surface or ceiling collapse Contamination Abandoned Mineral Lands (AML) features and sites	Potential Hazard (Moderate)	Atkinson (2016) DOI SHIRA Risk Mapper Report
Shrink/swell soils	Damage to infrastructure “Heaving” of ground beneath roads, trails, or structures Increased susceptibility to slope movements	Known Hazard	US Department of Agriculture (USDA) Web Soil Survey USDA, Natural Resources Conservation Service (NRCS), and DOI Soil Survey (2011)
Coastal storm surge/ sea or lake level change/shoreline erosion	Not applicable	Not applicable	Not applicable
Tsunami	Not applicable	Not applicable	Not applicable

Hazard	Examples of Risk or Secondary Hazard	Best Professional Judgment	Sources of Geohazard Information
Riverine Flood	Flooding (e.g., snowmelt, rainfall, and rain-on-snow) Destruction of infrastructure Stream channel migration Stream bank erosion Human injury or casualty	Known Hazard (Extreme)	DOI SHIRA Risk Mapper Report Federal Emergency Management Agency (FEMA) Map Service Center
Flash Flood	Sudden rising water (i.e., dry wash or tributary valley) Enhanced tributary flow regime and erosion capable of carrying large boulders Destruction of infrastructure Human injury or casualty	Known Hazard (Extreme)	GSRI GIS hazard layers or slope movement deposits (e.g., “rockfall deposits,” “colluvium and colluvial-fan deposits”) Maxwell (1968) Nadeau et al. (2014)
Volcanic eruption	Not applicable	Not applicable	Not applicable
Hydrothermal activity	Not applicable	Not applicable	Not applicable
Radon	Health hazard	Potential Hazard (Moderate – Zone 2)	US Environmental Protection Agency (EPA) Map of Radon Zones
Mercury contamination	Health hazard	Potential Hazard	Gray et al. (2008)
Toxicological soil (arsenic, <i>Bacillus anthracis</i> [causes anthrax], cadmium, lead, selenium)	Health hazard	Potential Hazard (High)	DOI SHIRA Risk Mapper Report

Flooding and Flash Flooding

The Rio Grande and its tributaries are important features of the national park’s landscape, as they drain the uplands, incise their geologic surroundings, carry vital nutrients, and provide a valuable source of water. However, recurrent seasonal flooding and flash flooding happen during the late summer and fall when BIBE experiences an increase in precipitation. Heavy storms combined with low-permeability soils produce a torrent of water that quickly overwhelms tributary valleys, resulting in flash flooding. According to Nadeau et al. (2014), more than 45% of the soils in the Big Bend region have slow or very slow infiltration rates, suggesting a large portion of the national park has high runoff potential. During flash flooding events, increased precipitation and runoff strengthen tributary flow and erosion, producing a large amount of sediment and debris that is transported towards the Rio Grande. Two of the BIBE’s famous geologic features—the Burro Mesa Pour-off and the Window—are seasonal waterfalls that experience increased discharge during flash flooding episodes. At the Window, Oak Creek typically has little or no water in the gorge during most of the year, but with heavy rains, the creek rapidly swells in size and intensity. The power of flash flooding along Oak Creek is recorded by large masses of rock that have been carried over the threshold and deposited at its base as rock fall deposits (**Qrf**). To quote BIBE’s first superintendent, Ross Maxwell:

At such times, the banging and bouncing of the rocks makes a terrific roar as the rock load grinds forward. At the Window's brink, one can see the boulders bounce like corks as they are pushed over the edge to drop 75 feet to the bottom of the falls below, where there is a great pile of bouldery debris. When Oak Creek is in flood stage, there is little doubt that stream erosion excavated the Basin and carved the narrow Window slit through the massive intrusion that walls the Basin on its north and west sides. (Maxwell 1968, p. 79)

Heavy thunderstorms and flash flooding increase tributary discharge into the Rio Grande, which causes periodic flooding that impacts low-elevation regions adjacent to the river corridor and creates potentially dangerous conditions. Many locations adjacent to the Rio Grande are situated within the 100-year floodplain of the river, a designation that predicts which areas could experience one major flood event every century (or a 1% annual chance; see <https://www.fema.gov/flood-maps/national-flood-hazard-layer>; accessed June 2024). At Santa Elena Canyon, flooding inundates portions of the trail and can leave visitors stranded and in need of rescue. Historic flooding in 1932 engulfed the Langford family bath house (now the foundational stones of Langford Hot Springs). Modern flooding still impacts the Hot Springs district as the Rio Grande continues to encroach upon and damage the trail, as well as fill the hot springs with sediment. Over the last several years, heavy thunderstorms and flooding have impacted several areas of BIBE, including Santa Elena Canyon in May 2017, September 2020, and May 2023; Tornillo Creek in August 2017 and May 2022; Tuff Canyon in June 2021; Terlingua Creek in June and August 2021; and the Hot Springs district in June 2022 and May 2023.

Disturbed Lands

Disturbed lands are those park lands where the natural conditions and processes have been directly impacted by development, including facilities, mining, roads, dams, and abandoned campgrounds; agricultural activities such as farming, grazing, timber harvest, and abandoned irrigation ditches; and overuse or inappropriate use. Restoration returns a site, watershed, or landscape to some previous condition, commonly some desirable historic baseline. Usually, lands disturbed by natural phenomena such as landslides, earthquakes, floods, and fires are not considered for restoration unless influenced by human activities. Human activity often disturbs lands, leading to unwanted and long-lasting problems that affect other resources. Many of these disturbances obliterate soil profiles, exacerbate the invasion of exotic plants, contaminate water and soil, and/or cause erosion and sedimentation. These damages, in turn, frequently impair habitat quality, disrupt ecosystem functions, and cause problems for managing areas as wildlands.

Historic Ranching

Prior to the establishment of the national park, the Big Bend region was ranched, which altered several aspects of the landscape, including its ecosystems, hydrology, soils, and erosion rate. Overgrazing by sheep and cattle, combined with associated stock tanks and water diversions, led to the removal of vegetation cover, negatively impacting grasslands throughout BIBE, especially in the Tornillo Flats area. As grass and other vegetation were removed, soils developed into physical crusts that reduced the infiltration of water, increased overland flow, concentrated runoff, and facilitated the development of extensive gully systems. Without vegetation, soils were more vulnerable to wind and gully erosion that removed them from the area (Ozaki 2003).

Today, grazing practices continue to modify BIBE's resources as livestock (e.g., burros, cows, horses, sheep) trespass across the international Rio Grande boundary (Ozaki 2003; National Park Service 2018). In the past, the Rio Grande served as a natural barrier to livestock trespassing, but increased water consumption and diversion have reduced the flow of the river, making it easier to cross. Once inside the national park, livestock promote enhanced erosion through grazing and trail development that can impact natural, archeological, and paleontological resources (Ozaki 2003).

Abandoned Mineral Lands

The history of mercury mining in and around BIBE presents a potential hazard related to pollution emanating from abandoned mines near Mariscal Mountain and along the Terlingua Creek drainage area (Welsh 2002; Gray et al. 2008). Some of the most significant environmental and health concerns associated with these mines are related to mercury contamination in mine waste, sediment, and soil in proximity to the mines. An additional concern is the possible release of mercury gas. The extraction of elemental mercury followed an

inefficient and incomplete process called “retorting,” in which quicksilver or cinnabar was heated in a furnace to about 600°C–700°C (1,110°F–1,300°F; Gray et al. 2008). After ore processing, mine waste with highly elevated mercury concentrations can leach into soils or solubilize in water and be transported downstream. According to Gray et al. (2008), more than 2,000,000 m³ (70,600,000 ft³) of mine waste remains in the Terlingua district, and about 30,000 m³ (1,060,000 ft³) remains at the Mariscal mine. Although mercury concentrations in mine waste are elevated at these sites, these levels progressively dissipate away from the mines. With respect to mercury contamination, only minor transference to the surrounding environment has been detected in downstream sediment and water samples (Gray et al. 2008). However, the current lack of infrastructure at the Mariscal mine prevents the erosion and downslope movement of mine waste, which may allow waste material to enter adjacent stream beds in the future.

In addition to potential mercury contamination, these historic mining operations cleared a considerable number of trees from the national park’s landscape (Don Corrick, Big Bend National Park geologist, personal communication, 25 March 2024). Wood from harvested timber was used to fuel the furnaces needed to extract elemental mercury from the cinnabar ore. Similar to overgrazing practices, the removal of trees negatively impacted soil health, structure, and stability, resulting in enhanced erosion.

Mass Wasting

The term “mass wasting” is used to describe downhill movements of rock or soil and includes landslides, slumping, slope creep, rock falls, and debris flows. Mass wasting events are driven by natural processes such as erosion, precipitation, flooding, and seismicity (earthquakes), but they can also be artificially induced by construction, mining, undercutting, vegetative clearing, and other projects that destabilize the ground.

The modern landscape and topography of BIBE are the result of dynamic erosional processes that include fluvial incision, flooding, preferential weathering (the selective breakdown of less competent rocks), thermal expansion/contraction, frost wedging, and hydrothermal dissolution. Each of these erosional processes has the potential to generate mass wasting events. The Rio Grande was introduced to the Big Bend region during the Pleistocene Epoch about 2 million years ago, and its development is recorded in steep canyons like Santa Elena Canyon, which contain large rockfall deposits (**Qrf**) with boulders close to 6 m (20 ft) in diameter. A notable and historic “rockslide” in the lower canyon consists of a large pile of rock approximately 75 m (250 ft) high and nearly 400 m (1,300 ft) long that has partially constricted the Rio Grande. It was along this segment of the river where R. T. Hill (USGS) and crew spent three days carrying their boats and supplies while exploring the US–Mexico boundary in 1899 (see “Other Notable Figures to Big Bend”). At Boquillas Canyon, the combination of moisture, thermal expansion/contraction, and frost wedging has produced vertical joints that occasionally dislodge blocks of limestone. Throughout the Chisos Basin, preferential weathering has removed softer volcanic ash and sandstone beds that underlie more resistant lava flows, causing volcanic cliffs to retreat as rock fragments fall into the valleys below. Similar processes have occurred at Boulder Meadows and in a 2014 rockfall that damaged the Laguna Meadow Trail.

Aside from rockfalls, preferential weathering has made bedrock slopes less stable, which has led to Quaternary-age landslide complexes (**Qls**) and colluvium deposits (**Qc**). Some of the major landslide deposits in BIBE are located in the Chilicotal and Talley Mountains, along the northwest flank of the Chisos Mountains, and on the northeast flank of the Rosillos Mountains (Turner et al. 2011). These landslides are characterized by irregular, hummocky surfaces and disrupted strata and typically occur where more resistant rocks overlie, or are adjacent to, less resistant Cretaceous sedimentary rocks (Turner et al. 2011). Landslides in the Chilicotal and Talley Mountain areas consist of Tertiary sill material (**Tir**) that has failed and slid over weaker mudstones and shales of the Cretaceous Javelina Formation (**Kj**) and Cretaceous–Paleocene Black Peaks Formation (**KTbp**). Additional smaller landslides have occurred throughout the Chisos Basin and on the flanks of Mesa de Anguila, Burro Mesa, Painted Gap Hills, Punta de la Sierra, and Sierra del Caballo, as well as Dagger, Kit, Trap, Goat, Little Christmas, Rosillos, and Slickrock Mountains.

Swelling Clays

As volcanic ash deposits are weathered, they are physically and chemically altered to swelling clays (clay minerals such as smectites that expand when water-saturated and contract upon drying) that pose a significant management issue and known hazard at BIBE. As these clay minerals swell and shrink in the presence of water, the constant change in volume undermines the integrity of the substrate, increases the susceptibility of slope failure, and causes infrastructural problems along roadways. Data from the NRCS Web Soil Survey indicates that several soils within BIBE are rated moderate to severe in linear extensibility (a determination of shrink-swell potential of soils), meaning they can cause damage to buildings, roads, and other structures.

Anthropogenic modifications that redirect the flow of water should consider the distribution and extent of swelling clay deposits—especially bentonite (a type of swelling clay)—as these activities can impact national park infrastructure (Ozaki 2003). One example of how human development was impacted by swelling clays occurred at the Chisos Basin Visitor Center. Throughout the basin, large sections of parking lots and roadways were paved without adequate planning with respect to drainage or runoff. As a result, water generated as runoff was directed downslope along the pavement surface until it flowed beneath the Visitor Center. The foundation of the Visitor Center was constructed on top of bentonite deposits, which expanded in response to the runoff, causing the building to heave and inducing serious structural problems (Ozaki 2003). To help remediate the problem, an improved drainage design was implemented that involved the construction of a drop inlet to catch and redirect runoff away from the building through a buried culvert. Swelling clays also compromised the foundation of the Chisos Mountains Lodge, causing the foundation to fail and requiring the demolition and replacement of the entire building (Don Corrick, Big Bend National Park geologist, personal communication, 30 August 2024). Additionally, in the early development of the Chisos Basin, swelling clays exposed in a road cut were collected and used as fill material, which can create several problems if these clays are transported to a more susceptible location.

Seismicity

The Trans-Pecos region is considered one of the most seismically active areas in Texas. Although seismicity within BIBE is infrequent, a recent 2023 earthquake with a local magnitude of 3.7 occurred north of Burro Mesa near the headwaters of Alamo Creek (see <https://www.beg.utexas.edu/texnet-cisr/texnet>; accessed June 2024). According to Ozaki (2003), a seismograph was formerly stationed in the Visitor's Center; however, today there is no longer a seismograph located within the national park. Immediately west of the national park, there is an array of 10 seismic stations near Terlingua (<https://catalog.texnet.beg.utexas.edu/>; accessed October 2024). Regular earthquake activity occurs around the Rustler Hills, about 240 km (150 mi) north of BIBE, that is attributable to active oil and gas exploration in the Delaware Basin (see <https://earthquake.usgs.gov/earthquakes/map/?extent=18.81272,-133.68164&extent=53.8266,-56.33789>; accessed June 2024). According to the USGS national seismic hazard model (Petersen et al. 2023) and DOI SHIRA Risk Mapper, the national park is in an area considered to be of low earthquake probability relative to the rest of the country.

Given the tectonic and structural evolution of west Texas, there are numerous faults traversing BIBE that were previously active but lack evidence of modern seismicity. Stevens and Stevens (1989) interpreted the Dugout Wells fault, on the east flank of the Chisos Mountains, to be active based on offset caliche horizons and disrupted stream drainages, but new surficial mapping has yielded no supportive data (Turner et al. 2011).

Climate Change

Although climate change planning is beyond the scope of this GSRI summary, a discussion of climate change is included because of the potential disruption it may cause to the national park's resources, including

geologic resources. In the Chihuahuan Desert, climate change and water availability are two major concerns for BIBE (Nadeau et al. 2014). While the summer and early fall are exceptionally hot and can lead to drought, they are punctuated by heavy thunderstorms that produce episodic flooding (see <https://www.nps.gov/bibe/planyourvisit/weather.htm>; accessed June 2024). The climate at the national park is already changing; all future climate model projections include temperatures above the recent historical average (1979–2012), and average annual precipitation is anticipated to be highly variable (Climate Change Response Program 2024). Projected increases of several variables (air temperatures, evaporation rates, extreme drought, extreme precipitation) may negatively affect aquifer recharge, spring or seep persistence, as well as the water quality and flow of the Rio Grande. These modifications to water availability are likely to impact additional geologic processes (e.g., floods, landslides, mudslides, erosion), in addition to ecological processes (e.g., invasive species, phenology), visitation, and park management procedures (National Park Service 2016; Raymond et al. 2022; Climate Change Response Program 2024).

Climate change manifestations that may intensify geologic hazards include the following:

- Increased average temperatures
- More intense drought
- More frequent and intense storms
- Increased susceptibility to flooding and mass wasting events
- Increased frequency and magnitude of fires
- Decreased water availability as groundwater sources dissipate

Radon

Radon is a naturally occurring gas created by the decay of radioactive elements present in many rocks. Although radon is almost always present in small amounts in soil and rocks, some types of rock (e.g., volcanic rocks, granites, dark shales, phosphate-rich rocks, and metamorphic rocks) have the potential to produce above average amounts of radon gas that can pose a known health risk (Otton 1992). According to the US Environmental Protection Agency (EPA) map of radon zones, Brewster County is identified as a zone of moderate potential (zone 2) for elevated indoor radon levels. National park staff have previously documented elevated radon levels in at least a couple of residences. One residence has been demolished and is being replaced, while the other has been kept vacant for an extended period, causing strain on the park's limited housing supply (Don Corrick, Big Bend National Park geologist, personal communication, 30 August 2024).

Toxicological Soil

According to the DOI SHIRA risk mapper report, the soils of BIBE include potentially dangerous amounts of arsenic, cadmium, lead, and selenium. They also contain *Bacillus anthracis*, a naturally occurring soil pathogen that is known to cause anthrax. Soil maps show that potentially hazardous elements occur within the top 5 cm (2 in) of soil based on 2010 sampling (DOI SHIRA). For more information on naturally occurring arsenic, cadmium, lead, and selenium and their potential health impacts, visit the US Department of Health and Human Services Agency for Toxic Substances and Disease Registry (see <https://www.atsdr.cdc.gov/>; accessed 26 June 2024). For more information on the public health risks associated with naturally occurring anthrax, visit the US Centers for Disease Control and Prevention's anthrax website (see <https://www.cdc.gov/anthrax/about/index.html>; accessed 26 June 2024).

Geologic Resource Protection

The core responsibility of the NPS is to preserve and protect park resources, processes, systems, and values unimpaired for present and future generations. According to National Park Service (2006), the NPS will preserve and protect geologic resources, features, and processes as integral components of park natural systems. The goals of the NPS are to assess the impacts of natural processes and human activities on geologic resources; maintain and restore the integrity of existing geologic resources; integrate geologic resources management into NPS operations and planning; and interpret geologic resources for the benefit and enjoyment of park visitors (National Park Service 2006). Various management protection policies applicable to geologic resources, features, and processes are included in National Park Service (2006) and are also organized at the following website: <https://home.nps.gov/subjects/geology/geoheritage-nps-management-policies.htm> (accessed 26 June 2024).

Paleontological and Archeological Resources

The national park's paleontological and archeological resources are invaluable and provide a unique window into the geological and historical past of the Big Bend region. Dynamic erosional processes can aid in the discovery of these resources, but they also have the potential to destroy or expose them to theft, vandalism, or neglect. The paleontological collections of BIBE are of outstanding value, containing several notable specimens and some of the best Cretaceous dinosaur fossils in the National Park System. Fossil research has been ongoing since the 1930s, and there is a consistent pace of new discoveries combined with a high paleontological potential for the future. Archeological sites and artifacts preserve a wealth of information about the Big Bend area, including a cultural continuum that records various human adaptations to the Chihuahuan Desert. Due to the remote, rugged nature of the desert landscape, only a small portion (about 10%) of BIBE has been investigated for cultural or archeological resources, and more discoveries are highly likely (Atkinson 2016; National Park Service 2016).

For additional information regarding paleontological resource laws, regulations, and policies, the NPS GRD developed the following summary article: <https://www.nps.gov/articles/paleontology-legal-instruments.htm> (accessed 26 June 2024).

Cave and Karst Vandalism

Several paleontological and archeological discoveries have been associated with the national park's cave and karst features. As a natural refuge, these sheltered environments were home to Indigenous Peoples and contain cultural resources that can help reconstruct the history of the Chihuahuan Desert, including its climactic, ecological, and human adaptations. However, the cultural landscape of BIBE is threatened by erosion, weathering, vandalism, illegal collecting, flooding, collapse, and neglect (National Park Service 2016). As annual visitation to BIBE increases, park management may seek to protect cave and karst features to better preserve the cultural continuum recorded in potential archeological deposits (Bousman and Rohrt 1974). Additionally, the study of invertebrate fossils within the caves of the Big Bend region is essentially nonexistent and merits further investigation (Atkinson 2016).

For additional information regarding cave and karst resource laws, regulations, and policies, the NPS GRD developed the following summary article: <https://www.nps.gov/articles/caves-and-karst-systems-legal-instruments.htm> (accessed 26 June 2024).

Groundwater Resources

In the arid Chihuahuan Desert environment, groundwater resources are critical features that help sustain ecosystems and landscape processes. There are several issues impacting BIBE's groundwater availability, as many of the aquifers, groundwater reservoirs, and surface waters have experienced declining trends due to climate change and aging infrastructure. Two of the main sources of drinking water in BIBE, Oak Springs

and the K-Bar aquifer, have been severely impacted by drought and groundwater withdrawal. Additionally, the water supply for the Chisos Basin and Oak Springs has shown significant flow reductions during the last several decades (National Park Service 2018).

Increasing population growth and development (e.g., agriculture, residential communities, and energy exploration and production) surrounding the national park has the potential to increase demand for water while also introducing sources of possible groundwater contamination or degradation. Further increases in human consumption will put additional strain on groundwater resources and will decrease the flow of the Rio Grande. The reduction of the Rio Grande flow impacts resources throughout BIBE, including ecosystems, flora and fauna, and visitor use of the park and river (National Park Service 2018).

Guidance for Resource Management

Please see the [GSRI SharePoint site](#) for additional guidance on geologic resource management.

Inventory Needs

Moving forward, the GSRI program will fund inventory projects that include the following:

- Collect new data or derive new information from existing data regarding the presence, absence, abundance, distribution, and significance of geologic heritage, soil features or processes, or geohazards.
- Provide information about features or processes on an individual feature or landscape scale.
- Provide data about groups of features or maps of multiple features in a defined area of management needs.
- Are a snapshot in time and may set a baseline for monitoring or assessment.
- Typically include a geospatial (GIS) component.

The following table (Table 4) presents geologic and soil resource inventory needs that were identified during the 2024 follow-up meeting, in NPS planning documents, or through literature review.

Table 4. List of identified geologic and soil resource inventory needs for the national park.

Subject	Inventory Need(s)	Reference(s)
Cultural resources	Cultural GIS data update.	National Park Service (2016)
Cultural resources	Baseline cultural resource/landscape inventory.	National Park Service (2016, 2018)
Cultural resources	GIS model for protection of cultural sites.	National Park Service (2016)
Cultural resources	Survey remaining cultural sites, particularly along riparian corridors.	National Park Service (2016)
Paleontological resources	Need to quantify the erosion rates in badlands-type terrain with paleontological resources. Identify the rate of exposure and destruction of new fossils (i.e., number of specimens eroded in a given time).	Ozaki (2003); 2024 follow-up meeting

Subject	Inventory Need(s)	Reference(s)
Paleontological resources	Determine whether livestock grazing and trail networks are accelerating erosion and impacting paleontological resources. Use historic air photos to look at erosion over time. Investigate the use of the Intelligent Laser Ranging Imaging System (ILRIS) as a monitoring tool to determine erosion rates.	Ozaki (2003)
Stratotype resources	Baseline condition and stability assessment, including unstable slope management program evaluation, and use of photogrammetry.	Henderson et al. (2021)
Stratotype resources	Establish a routine monitoring plan to identify threats or impacts.	Henderson et al. (2021)
Stratotype resources	Work toward establishing stratotypes for several formally named units mapped within the national park (e.g., Eocene Exhibit Sandstone Member of the Hannold Hill Formation; Eocene–Oligocene Big Bend Park Group and Chisos Formation; Miocene Smoky Creek Member of the Delaho Formation).	Henderson et al. (2021)
Cave and karst	The archeological, cultural, and paleontological resources of Big Bend’s cave and karst features are relatively unknown.	Atkinson (2016)
Cave and karst	The study of invertebrate fossils within the caves of the Big Bend region is essentially nonexistent and merits further investigation.	Atkinson (2016)
Hydrology	Study the Rio Grande’s sedimentation processes—including identifying major sources of fine sediment and the volume of sediment they contribute—and understand the interactions between stream flow, sediment transport, channel migration, and channel narrowing.	Ozaki (2003); Nadeau et al. (2014); National Park Service (2016, 2018)
Hydrology	Little research has been done on small, isolated, and often ephemeral springs. A better understanding of the typical processes, patterns, and ecological interactions at these unique sites would help managers maintain them and assess their condition.	Nadeau et al. (2014)
Hydrology	Comprehensive channel and floodplain measurement and monitoring program. Environmental monitoring of river conditions; understand park developments and relationship with floodplain (Route 16, culverts, road alignments, backcountry campsites, river access, etc.).	National Park Service (2016)
Hydrology	Need to determine the capacity of existing groundwater wells and springs in BIBE to help determine the capacity of existing groundwater resources to support future national park developments. Need to evaluate the BIBE’s aquifers, determine pump rates, and monitor water levels.	Ozaki (2003)
Disturbed lands	Update the cross-border impacts report.	National Park Service (2016)
Disturbed lands	Need to establish and quantify erosion from livestock trails in BIBE and assess the impacts on the national park’s natural resources.	Ozaki (2003)

Subject	Inventory Need(s)	Reference(s)
Mass wasting	Need to establish a park-wide geohazard assessment (i.e., rockfalls, debris flows, flooding).	2024 follow-up meeting
Mass wasting	Create an unstable slope management program evaluation of high-risk areas.	2024 follow-up meeting
Soils and soil erosion	Collect data on bentonite clay distribution, which would be helpful in mitigating swelling clay issues.	2024 follow-up meeting
Soils and soil erosion	Inorganic nitrogen accumulation studies within BIBE are limited. Further research is needed to understand the impacts of too much or too little nitrogen on BIBE's soils and plant communities.	Nadeau et al. (2014); National Park Service (2016)
Soils and soil erosion	Data on soil aggregate stability and soil crusts have only been gathered in a small portion of BIBE (North Rosillos) where erosion is a concern and have not been published. These data may be available from the NRCS for future assessments.	Nadeau et al. (2014)
Soils and soil erosion	Research into how various activities (e.g., recreation, development) affect BIBE soils could be helpful for park managers.	Nadeau et al. (2014)
Soils and soil erosion	Further research is needed on the distribution and impacts of invasive species on the desert grasslands, historical grassland extent, erosion rates in the national park, and methods for desert grassland restoration.	Nadeau et al. (2014); National Park Service (2018)
Soils and soil erosion	Although microbial crusts are believed to contribute organic matter that benefits soil health, their extent, distribution, and colonization rate are currently unknown.	Ozaki (2003)
Soils and soil erosion	Need to establish photo points, longitudinal profiles, and cross sections for gully systems. Measure gully plots annually and track erosion rates. Also, estimate the long-term erosion rates for areas not subjected to heavy ranching and compare erosion rates to areas with extensive grazing.	Ozaki (2003)
Energy development	Collect data on oil and gas development in the region on both sides of the border and its possible impacts on water resources.	National Park Service (2016)
Climate change	Conduct a climate change vulnerability assessment.	National Park Service (2016)
Geoscience Research	Update geologic age dates for igneous units.	2024 follow-up meeting
Geoscience Research	Develop and populate a research catalog and list of research needs.	National Park Service (2016)

Prior NRSS-based Work

Geologic or Soil Research Permits

The following table (Table 5) is a list of completed research projects related to the geology or soils of BIBE. These items are located on the NPS Research Permit and Reporting System of IRMA (see <https://irma.nps.gov/RPRS/Search>; accessed May 2024) but may require government access or assistance. Since 2000, there have been numerous (>45) geoscience research permits issued that include geologic and geophysical mapping; stratigraphic, volcanogenic, tectonic, and paleontological investigations; resource monitoring (e.g., springs, seeps, fossils); hydrocarbon assessments; geoenvironmental studies; and geologic substrate impacts on vegetation.

Table 5. Research permits related to the geology or soils of BIBE since 2000.

Year(s)	Title
2001	Mapping, geologic, and biological survey of Mexican Long-nosed Bat Cave
2001	Regional paleoenvironmental reconstruction of the Cretaceous (Coniacian–Santonian) Western Interior Seaway, San Vicente Member, Boquillas Formation, and Pen Formation, Big Bend region, Trans-Pecos Texas
2001, 2002, 2003, 2004, 2005	Update of the soil survey of Big Bend National Park, Texas
2002	Volcanology of the Chisos Formation and structure of a dike swarm
2002	Mapping Tornillo Loam and associated vegetation communities in Big Bend National Park
2002	Collection of fossils and documentation and study of fossil localities, Late Cretaceous, Big Bend National Park, Texas
2002	Mapping, geologic, and biological survey of Mount Emory Cave
2003	Flora and vegetation associated with specific geological substrate, McKinney Hills, Big Bend National Park
2003	Geologic mapping, volcanogenic, geophysical, and geoenvironmental studies of Big Bend National Park
2004, 2006	Geologic mapping of the Cerro Castellan 7.5' Quadrangle, Big Bend National Park: volcanology and petrology of Burro Mesa Rhyolite and associated units
2005	Paleontology and stratigraphy of the Banta Shut-in Formation, Big Bend National Park
2005	Cyano-bacterial colonization of gypsum (CaSO ₄ ·2H ₂ O) plates: characterization of the hypolithic environment and interactions between bacteria and mineral substrate, Chihuahuan Desert: Big Bend National Park, Texas
2005	Stratigraphy and paleontology of the Boquillas Formation, Big Bend National Park
2008, 2009	Geologic map of Big Bend National Park (1:24,000 scale; Mariscal Mountain area)
2009	Geology of the Sierra Quemada caldera and petrology of the Mule Ear Spring Tuff
2009	Kinematic analysis of the Chalk Draw Fault, Big Bend National Park, Texas
2009	Late Cretaceous paleontology and geology of Big Bend National Park, Texas
2009	Mapping, stratigraphy and paleontology of the Boquillas Formation, Big Bend National Park/Lozier Canyon/Terlingua/Study Butte/Lajitas/Fresno Mining District
2009, 2010, 2016	Mapping folds and faults in Sierra Del Carmen, Big Bend National Park
2010	Inventory paleontological resources at Big Bend National Park, Texas
2011	Soil survey of Big Bend National Park, Texas
2011	Evidence for Laramide contraction and Basin and Range extension in the eastern Rosillos Mountains, Brewster County, Texas
2011	CHDN seep and spring monitoring

Year(s)	Title
2012	Stratigraphy and paleontology of the Tornillo Group (Upper Cretaceous–Eocene), south of Chisos Mountains, Big Bend National Park, Texas
2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023	CHDN uplands vegetation and soils monitoring
2014	Volcanic tuff and lava flow correlation in Big Bend National Park
2014	Vegetation and soil surveys related to salt cedar biological control
2015	Investigation of young Laramide shortening in Big Bend National Park
2015	Geologic evolution of Mariscal Mountain
2016	Investigating the ichnological response of soil-dwelling organisms to the K – Pg mass extinction: Big Bend National Park, Texas
2016	Strain analysis of mesostructures within the hinge zone of a footwall syncline in the Laramide fold-and-thrust belt of eastern Big Bend National Park, Texas
2016	Depositional environments of the Chisos Formation (Eocene), western Big Bend National Park, Texas
2016	Stratigraphy and paleontology of Upper Cretaceous–Paleogene strata in northern Mexico and adjacent Big Bend National Park, Texas
2017	US Geological Survey studies of naturally occurring CO ₂ and helium
2017	Structural geology and tectonic implication and evolution focused on the Ernst Tinaja Canyon, Big Bend National Park, Brewster County, Texas
2017	Geology of northern Alto Relex area, Roys Peak Quadrangle, Big Bend National Park, Brewster County, Texas
2020	Structural analysis and synthesis of the Chisos Pen region, Big Bend National Park
2021	Kinematic analyses of Rio Grande rift extension and Laramide drag folding in the Trans-Pecos region of western Texas and northern Chihuahua
2021	An investigation into the Late Cenomanian Ocean Anoxic Event 2 (OAE-2) and its chronostratigraphic correlation across the southern aperture of the Cretaceous Western Interior Seaway
2021	Observation of surface features on fracture faces in rocks
2021	Non-destructive analysis of funerary items from 41CR61

Previous or Ongoing Technical Assistance Requests

The following table (Table 6) provides previous or ongoing technical assistance requests submitted to the GRD related to the geology or soils of the national park. These items are located on the NPS Solution for Technical Assistance Requests (STAR) of IRMA (see <https://irma.nps.gov/STAR/>; accessed May 2024) but may require government access or assistance.

Table 6. Previous or ongoing geology or soils related technical assistance requests.

Year(s)	Title	Program Area
2010, 2011	Inventory Paleontological Resources at Big Bend National Park, Texas	Geologic Features, Processes, or Hazards
2011	Provide Paleontological Resource Protection Training and Paleontological Resource Monitoring Training	Geologic Features, Processes, or Hazards
2013	Inter-divisional technical training regarding identification and protection of paleontological resources in Big Bend National Park	Geologic Features, Processes, or Hazards
2013	Copy editing of BIBE 2013 Paleontological Resources Inventory	Geologic Features, Processes, or Hazards
2024	Geohazard and Engineering Assessment of Tuff Canyon Trail and Observation Platforms	Active Geologic Processes and Hazards

Primary Sources of Information and Acknowledgments

Primary Sources of Information

Key sources of information used in drafting the GSRI summary for BIBE include:

- Maxwell et al. (1967)
- Maxwell (1968)
- NPS Cave and Karst Resources Summary (Atkinson 2016)
- NPS Foundation Document (National Park Service 2016)
- NPS Geoindicators Scoping Report (Ozaki 2003)
- NPS GRI GIS data (source map of Turner et al. 2011)
- NPS Natural Resource Condition Assessment report (Nadeau et al. 2014)
- NPS Resource Stewardship Strategy Summary (National Park Service 2018)
- Turner et al. (2011)
- Wick and Corrick (2015)

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