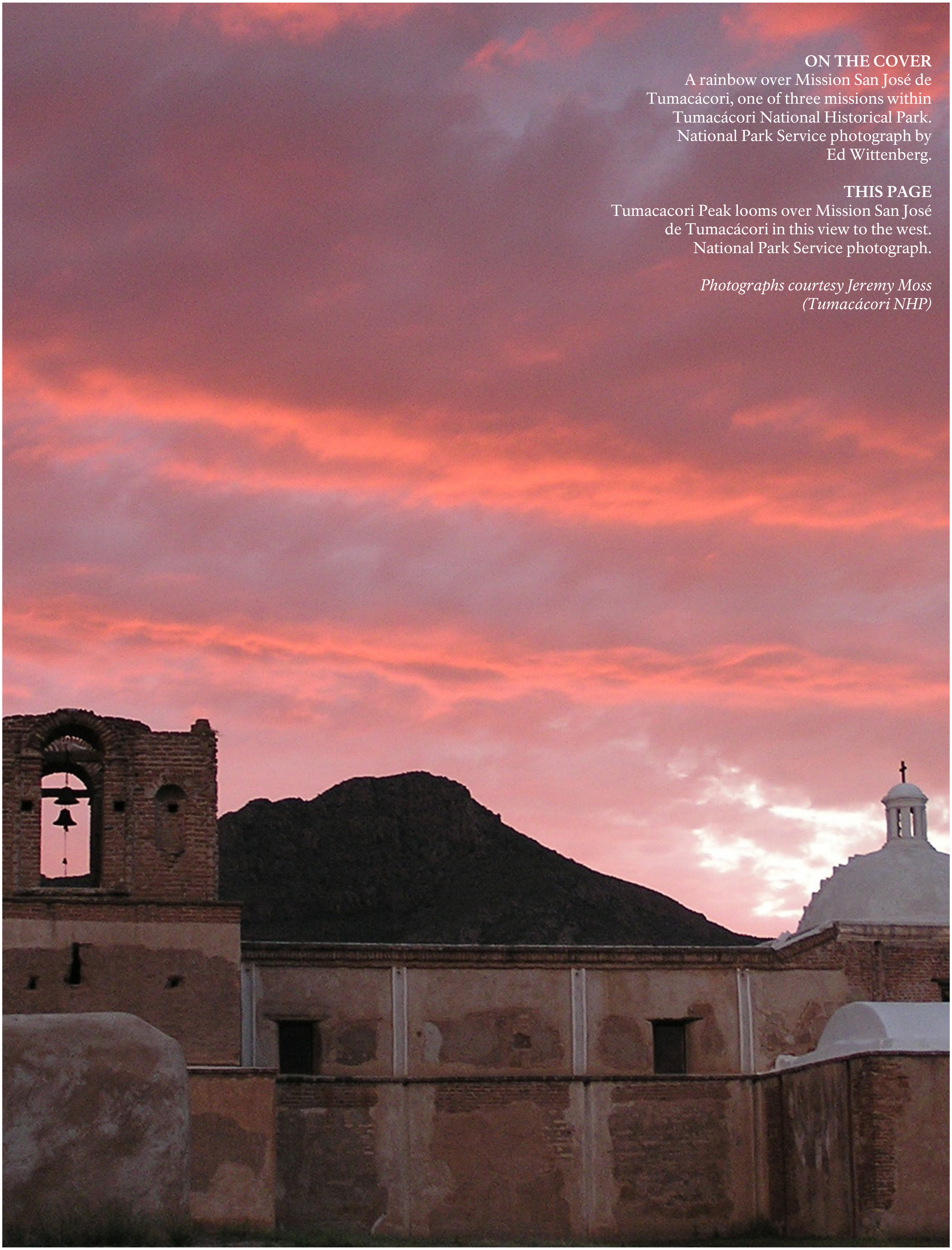
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Tumacácori National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/439



ON THE COVER
A rainbow over Mission San José de Tumacácori, one of three missions within Tumacácori National Historical Park. National Park Service photograph by Ed Wittenberg.

THIS PAGE
Tumacacori Peak looms over Mission San José de Tumacácori in this view to the west. National Park Service photograph.

Photographs courtesy Jeremy Moss (Tumacácori NHP)

Tumacácori National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/439

National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

August 2011

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

Please cite this publication as:

Graham, J. 2011. Tumacácori National Historical Park: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2011/439. National Park Service, Fort Collins, Colorado.

NPS 311/109539, August 2011

Contents

List of Figures

Executive Summary

This report accompanies the digital geologic map data for Tumacácori National Historical Park in Arizona, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

Tumacácori National Historical Park protects three Spanish colonial mission ruins that date to the eighteenth and nineteenth centuries: San José de Tumacácori, Los Santos Ángeles de Guevavi, and San Cayetano de Calabazas. The largest unit in the park is the Tumacácori Mission Unit, located on the banks of the northward-flowing Santa Cruz River. The unit contains a visitor center and museum, in addition to the mission church and associated ruins and archaeological sites. The Calabazas and Guevavi units, which are normally closed to the public, lie south of the Tumacácori Mission Unit. In 2002, a boundary expansion added critical desert riparian habitat along the Santa Cruz River to the park.

The following geologic issues are of particular significance for resource management at Tumacácori National Historical Park, as identified at the Geologic Resources Inventory scoping session held on April 4, 2006.

- Groundwater and surface water quality. Until the upgrade to the Nogales International Wastewater Treatment Plant in 2009, water quality in the Santa Cruz River did not meet Environmental Protection Agency standards. The upgraded treatment plant, located adjacent to the Calabazas Mission Unit at the confluence of Nogales Wash and the Santa Cruz River, meets some required permit limits, but heavy metal contamination remains an issue. The river maintains a permanent flow because of effluent released from the treatment plant, but this water source is not assured into the future.
- Flooding and debris flows. Storm events in southeastern Arizona commonly result in debris flows and flash flooding in the park. Increased flow velocity may laterally erode the unconsolidated sand and silt along the banks of the Santa Cruz River. Regionally disastrous floods in 1983, 2006, and 2008 caused extensive damage to communities on the Santa Cruz River, from Nogales to Tucson.

Tumacácori National Historical Park lies within the Basin and Range geological province, a landscape of alternating mountain ranges and flat valleys. The three units primarily contain unconsolidated sediment eroded from the surrounding mountain ranges. Tertiary and Mesozoic sedimentary and igneous rocks border the smaller Calabazas and Guevavi units. The rock units tell a story of violent volcanic eruptions, igneous intrusions, millions of years of erosion, and tectonic extension that pulled apart the crust.

The physical properties of the different geologic units mapped in Tumacácori National Historical Park are described in the map unit properties table. The table includes characteristics such as erosion resistance, suitability for infrastructure, geologic significance, recreation potential, and associated cultural and mineral resources for the geologic units mapped within the park.

This report also provides a glossary, which contains explanations of technical, geologic terms, including terms on the map unit properties table. Additionally, a geologic timescale shows the chronologic arrangement of major geologic events, with the oldest events and time units at the bottom and the youngest at the top. The timescale is organized using formally accepted geologic-time subdivisions and ages (fig. 18).

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

Special thanks to Jeremy Moss (Tumacácori National Historical Park) for providing photographs and information regarding the park's geological features and issues. Steve Gastellum (Tumacácori National Historical Park) provided information regarding hazardous waste issues in the park.

Credits

Author
John Graham (Colorado State University)

Review
Michael Conway (Arizona Geological Survey)
Jason Kenworthy (NPS Geologic Resources Division)
Jeremy Moss (Tumacácori National Historical Park)

Editing
Steve Hoffman (Write Science Right)

Digital Geologic Data Production
Ron Karpilo (Colorado State University)
Stephanie O'Meara (Colorado State University)

Digital Geologic Data Overview Graphic Layout and Design
Derek Witt (Colorado State University intern)
Andrea Croskrey (NPS Geologic Resources Division)
Philip Reiker (NPS Geologic Resources Division)
Georgia Hybels (NPS Geologic Resources Division)

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Tumacácori National Historical Park.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/).

Regional Information

Located north of Nogales in the upper Santa Cruz River Valley of southern Arizona, Tumacácori National Historical Park protects three Spanish colonial mission ruins: San José de Tumacácori, Los Santos Ángeles de Guevavi, and San Cayetano de Calabazas (figs. 1 and 2). The largest unit in the park is the Tumacácori Mission Unit with 134 ha (330 ac) (see cover). The Calabazas Mission Unit contains 9 ha (22 ac), and the Guevavi Mission Unit covers 3 ha (8 ac). The Calabazas and Guevavi units lie south of the Tumacácori Mission Unit (fig. 2).

Flowing north out of Mexico, the Santa Cruz River changes its course about 2.4 km (1.5 mi) north of Nogales to flow northwesterly between canyons cut into the western slopes of the Patagonia Mountains and the northern and eastern slopes of Mount Benedict. The Guevavi Mission Unit lies in the river valley between Comoro Canyon and Burro Canyon. The Santa Cruz River maintains this course for approximately 16 km (10 mi) until its confluence with Nogales Wash, about 14 km (9 mi) north of the international border

The Calabazas Mission Unit is located at the confluence of the Santa Cruz River and Nogales Wash. Across the river to the south is the Nogales International Wastewater Treatment Plant, which treats wastewater from Nogales and Mexico. Effluent from the treatment plant maintains a permanent flow in the river.

At its confluence with Nogales Wash, the Santa Cruz River establishes a northward flow through the Santa Cruz Valley and past the Tumacácori Mission Unit. In addition to the mission ruins, the Tumacácori Mission Unit contains the park visitor center and museum. The Tumacácori Mission Unit remains open to the public every day except Christmas and Thanksgiving. Special tours during the winter months provide access to the Calabazas and Guevavi units, which are normally closed to the public.

The boundary expansion of 2002 added 1.6 km (1 mi) of critical desert riparian corridor along the Santa Cruz River to the park. The corridor protects a rapidly disappearing habitat of mature mesquite-bosque and cottonwood-willow forest.

Regional Geologic Setting

Tumacácori National Historical Park lies within the Basin and Range geological province that extends from northern Mexico to southeastern Oregon (fig. 3). This basin-and-range landscape, which is unique to North America, began forming approximately 15 million years ago when tectonic forces began extending (pulling apart) the crust. North-south trending structural basins, called "grabens," separate adjacent mountain ranges, known as "horsts" (figs. 3 and 4). Regionally extensive, north-south trending normal faults form the borders of grabens (fig. 5). Rocks and sediments in the basins have moved down along the faults relative to mountain blocks.

Normal faults separate the Tumacácori Mission Unit, located in the Santa Cruz Graben, from the San Cayetano Mountains to the east and the Tumacácori Mountains to the west (Drewes 1980). The surfaces of the faults have been covered by sediment eroded from the respective mountains. The bend in the Santa Cruz River north of Nogales follows another normal fault, one that branches to the southeast from the main basin-bounding fault along the eastern border of the Santa Cruz Graben (Drewes 1980). Mount Benedict forms a horst between the Santa Cruz River and the southern extension of the Santa Cruz Graben (fig. 6). The Calabazas Mission Unit lies near the juncture of the two faults (see the Overview of Digital Geologic Data graphic). The Guevavi Mission Unit lies within the fault zone that influenced the Santa Cruz River channel morphology.

Elevations between the mountain ranges and the valley floors change dramatically in the Basin and Range Province. For example, within a horizontal distance of 1.6 km (1 mi) west of Tumacácori Mission, the Tumacácori Mountain front rises abruptly to 1,500 m (5,000 ft), from an elevation of 1,000 m (3,400 ft) at the basin's western margin (see inside front cover). Along the Santa Cruz River, the Tumacácori Mission Unit lies at an elevation of approximately 910 m (3,000 ft). The Santa Cruz River adjacent to the Guevavi Mission flows at an elevation of approximately 1,000 m (3,500 ft). The summit of Mount Benedict, about 2.4 km (1.5 mi) west of the mission, is 1,390 m (4,560 ft) above sea level.

Since the origin of the basin-and-range landscape, a tremendous amount of material has been eroded from the mountains and deposited in the adjacent basins. In just the past 5 to 3 million years, approximately 800 m (2,600 ft) of sediment has been deposited in the Santa Cruz Graben (Drewes 1980; fig. 6). The surface geology of Tumacácori Mission Unit consists of Holocene (11,700 years ago to present) floodplain, terrace, and modern river channel deposits that have been eroded from the surrounding highlands (fig. 7).

Volcanic rocks from volcanic eruptions that occurred from 27 to 23 million years ago form the landscape of the Tumacácori Mountains. Lava flows and material exploded from volcanic vents (pyroclastics) are commonly a few tens to a few thousands of meters thick (Drewes 1980).

Mesozoic (251 to 65.5 million years ago) rocks are exposed in the San Cayetano Mountains, east of the Santa Cruz Graben basin-bounding fault, and on the slopes and summit of Mount Benedict, adjacent to the Calabazas and Guevavi Mission Units (Simons 1974, Drewes 1980, Youberg and Helmick 2001). The Calabazas Mission Unit contains exposures of the Salero Formation, a unit of sandstone, conglomerate, and volcanic material (tuff) deposited approximately 75 to 70 million years ago during the Late Cretaceous Period (99.6 to 65.5 million years ago) (Drewes 1968).

The oldest rocks in Tumacácori National Historical Park are granitic rocks that form Mount Benedict and the southern border of the Guevavi Mission Unit (fig. 7). These igneous, intrusive rocks record a radiometric age of 164 to 160 million years, during the Jurassic Period (Drewes 1980). Because they have equal proportions of plagioclase and potassium feldspar minerals (about 36% each) and 20% quartz, the rocks are classified as "quartz monzonite."

The riparian (streamside) environment of the Santa Cruz River consists of modern floodplain and river sediments that have been deposited adjacent to the Santa Cruz River and its tributaries. In the seventeenth and eighteenth centuries, the lush Santa Cruz River Valley provided excellent natural resources for the American Indians, Spanish missionaries, prospectors, and ranchers who migrated into the area.

Cultural History

Prior to the O'odham culture, southern Arizona was occupied by the Hohokam. Farmers of corn, beans, squash, agave, and cotton, the Hohokam lived in the region for nearly 1,500 years ending about 1450 CE (Common Era). To irrigate their fields, they built canals, and these canals were later excavated and used by pioneer farmers in historic times. From the canals, they harvested shellfish and fish. Having no domesticated livestock, the Hohokam hunted game such as deer, rabbit, and quail. Throughout southern Arizona, the Hohokam carved hundreds of petroglyphs. They left behind pottery, stone tools, and woven cotton textiles (Tempe History Museum 2010).

The Trincheras culture also occupied the southern regions of the American Southwest and Northwest Mexico. Contemporary with the Hohokam, the Trincheras inhabited the Altar and Magdalena River valleys of northwestern Sonora from 800 to 1300 CE, although their culture extended into southern Arizona (Arizona State Museum 2010).

When Spanish missionaries entered southern Arizona in the seventeenth and eighteenth centuries, they found the region occupied by the O'odham culture. As Spain's domain expanded into South America, Central America, present day Mexico, and North America, the Spanish Crown sent Jesuit priests into what is now southern Arizona to establish missions and convert the indigenous people to Christianity. To the Spanish, the O'odham Indians were known as Pimas. The lush river valleys that were home to the O'odham communities became known as Pimería Alta, "place of the upper Pimas" in English (fig. 8) (National Park Service 2006a).

Padre Eusebio Francisco Kino became the first Jesuit priest to enter the Pimería Alta. In 1691, Padre Kino established Mission San Cayetano de Tumacácori and Mission Los Santos Ángeles de Guevavi, the first missions established in what is today Arizona. Over the course of 24 years, Padre Kino established 24 missions and visitas (missions in which the priest is not in residence, but visits on a regular basis) and built the foundation for modern agriculture and raising livestock. Padre Kino died in 1711, and Jesuit priests continued his work. They established the Calabazas mission in 1756.

Very little remains today of the structures built by Padre Kino. Some of the churches seen today at the missions are the work of Franciscan missionaries who entered the area in the early nineteenth century, or of modern-day builders. The Guevavi church visible today was entirely Jesuit construction (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, August 25, 2011). The mission at Tumacácori was renamed San Jose de Tumacácori when the mission was moved to the west side of the river following the Pima Revolt of 1751. The Franciscans consecrated the present church in 1822 although construction continued into the 1840s (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, August 25, 2011). At one time, Tumacácori mission raised 5,000 cattle, 2,700 sheep and goats, and 750 horses and mules.

Spanish and Basque prospectors and ranchers began moving into the rugged mountainous area south of Tumacácori in the mid-1730s. Bernardo de Urrea, a Basque from Culiacán, Mexico, started a ranch, which he named Arizona. Eventually, Urrea became a deputy chief justice for the area, and the political jurisdiction also became known as Arizona. "Arizona" became further established when miners developed a Royal Mining Camp called "Agua Caliente," near Urrea's ranch, which became known as the "Agua Caliente of the Arizona" (National Park Service 2006a).

Guevavi Mission was abandoned in 1775 following a number of attacks by Apaches in 1769, 1770 and 1771. Apaches set fire to the church, houses, and granary at Calabazas Mission in 1777. Continued conflict lead to abandonment of the mission in 1786.

When Mexico won its independence from Spain in 1821, missionaries who had been born in Spain were asked to leave by the new Mexican government. Following the Treaty of Guadalupe Hidalgo on February 2, 1848, more Spanish missions closed. In December 1848, Tumacácori was abandoned by American Indians who stayed at the mission after the padres departed (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, August 25, 2011).

Over time, homesteaders encroached onto the mission lands, so that by the time the 4 ha (10 ac) of Tumacácori National Monument were authorized by President Theodore Roosevelt in 1908, all of the former mission lands were in private ownership. The Tumacácori Visitor Center and Museum, built in 1937, was placed on the National Register in 1987. Congress authorized the Guevavi and Calabazas Units in 1990, and changed the designation to Tumacácori National Historical Park. In 2002, Congress authorized an additional 125 ha (310 ac) surrounding the Tumacácori Unit. For more information regarding the history and structures of Tumacácori National Historical Park, visit the NPS Park Histories page: http://www.nps.gov/history/history/park_histories/index.htm#t (accessed June 10, 2010).

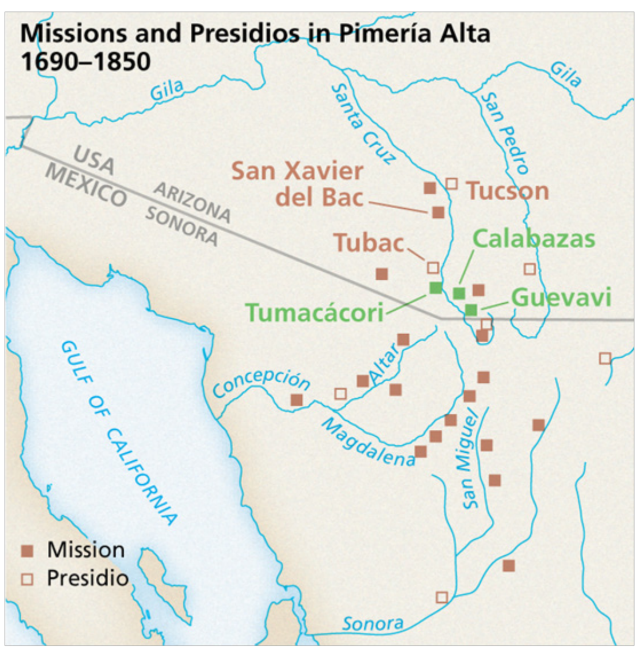


Figure 1. Map showing the missions and presidios of the Pimería Alta. The three missions of Tumacácori National Historical Park are colored in green. National Park Service map.

Figure 2. Ruins of San Cayetano de Calabazas (top) and Los Santos Ángeles de Guevavi (bottom) missions. The third, namesake mission of the park, San José de Tumacácori, is pictured on the cover and inside cover of the report. National Park Service photographs courtesy Jeremy Moss (Tumacácori National Historical Park).

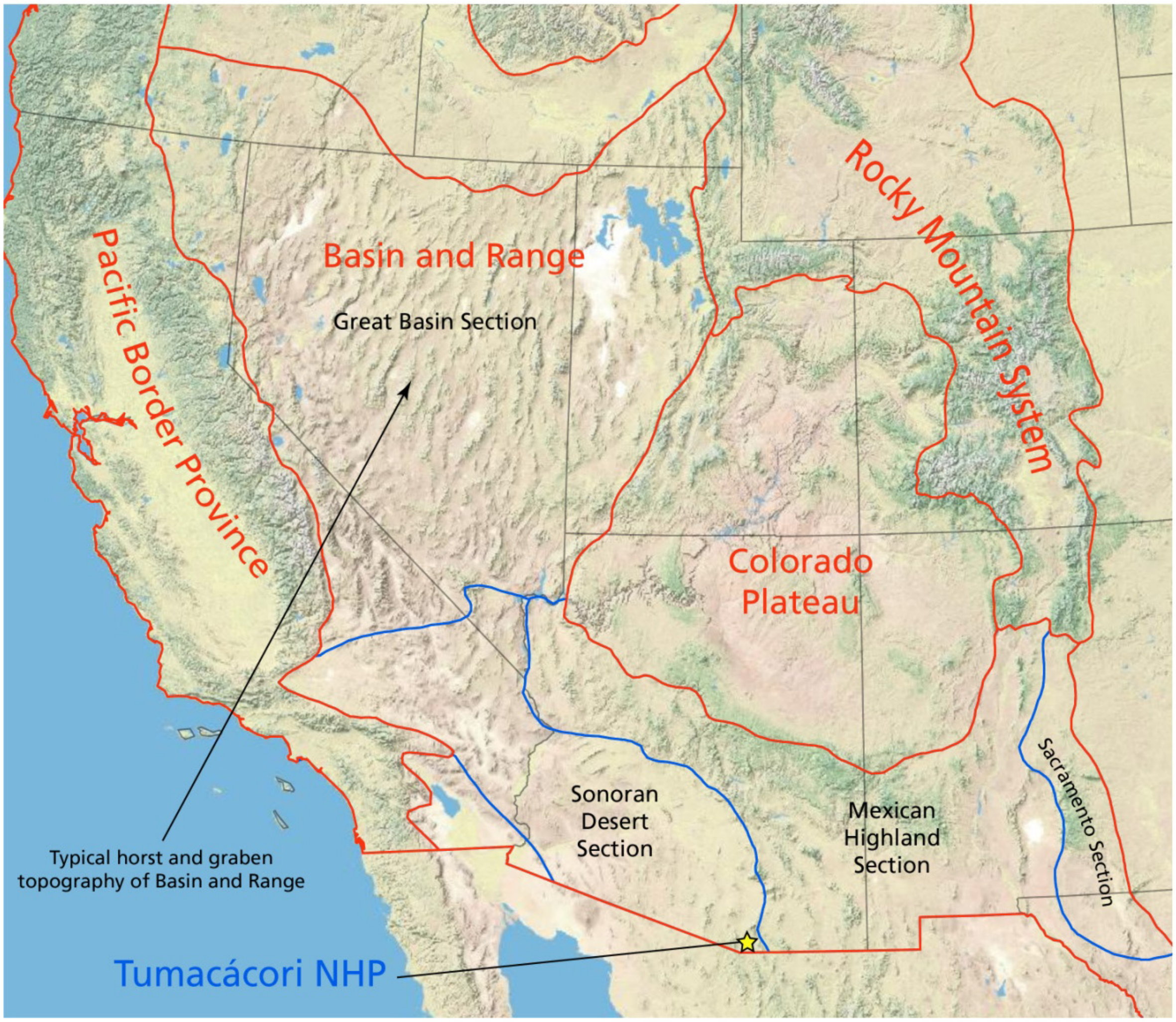


Figure 3. Basin and Range Province of the western United States. Tumacácori National Historical Park (yellow star) lies near the transition zone between the Sonoran Desert and the Mexican Highland portion of the Basin and Range. Note the distinctive basin-and-range topography of elevated mountain ranges bordering flat basins, particularly in the Great Basin section. Geologist Clarence Dutton referred to this topography as "caterpillars crawling north out of Mexico." The ranges are uplifted "horsts" while the basins are down-dropped "grabens" separated by normal faults (see figs. 4 and 5). Compiled by Philip Reiker (NPS Geologic Resources Division) from ESRI Arc Image Service, National Geographic Society TOPO Imagery.

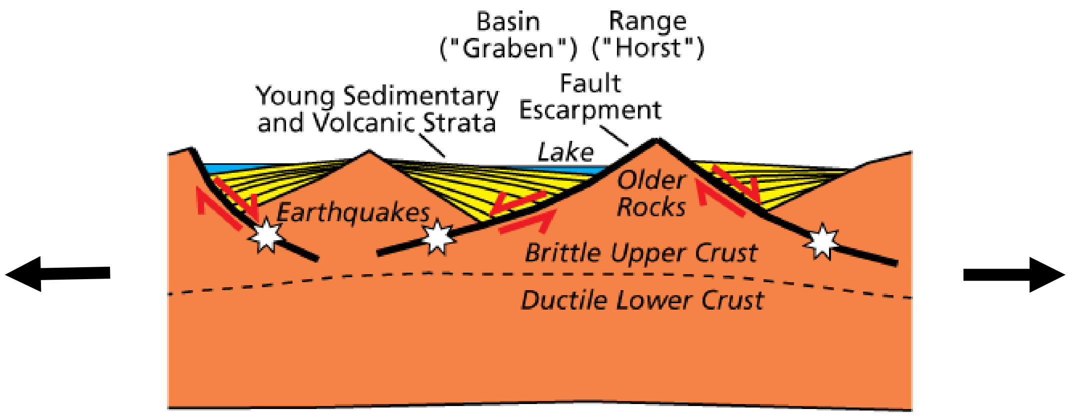


Figure 4. Horst and graben structure of the Basin and Range Province. Extension (black arrows) pulls apart the crust, promoting normal faulting (fig. 5). Horsts are uplifted blocks of rock while grabens are dropped down relative to the horsts. The grabens fill with sediments eroded from adjacent mountain ranges. Tilting of the land surface may result in lakes ponded against the adjacent fault escarpment. Diagram by Robert J. Lillie (Oregon State University), modified from Lillie (2005).

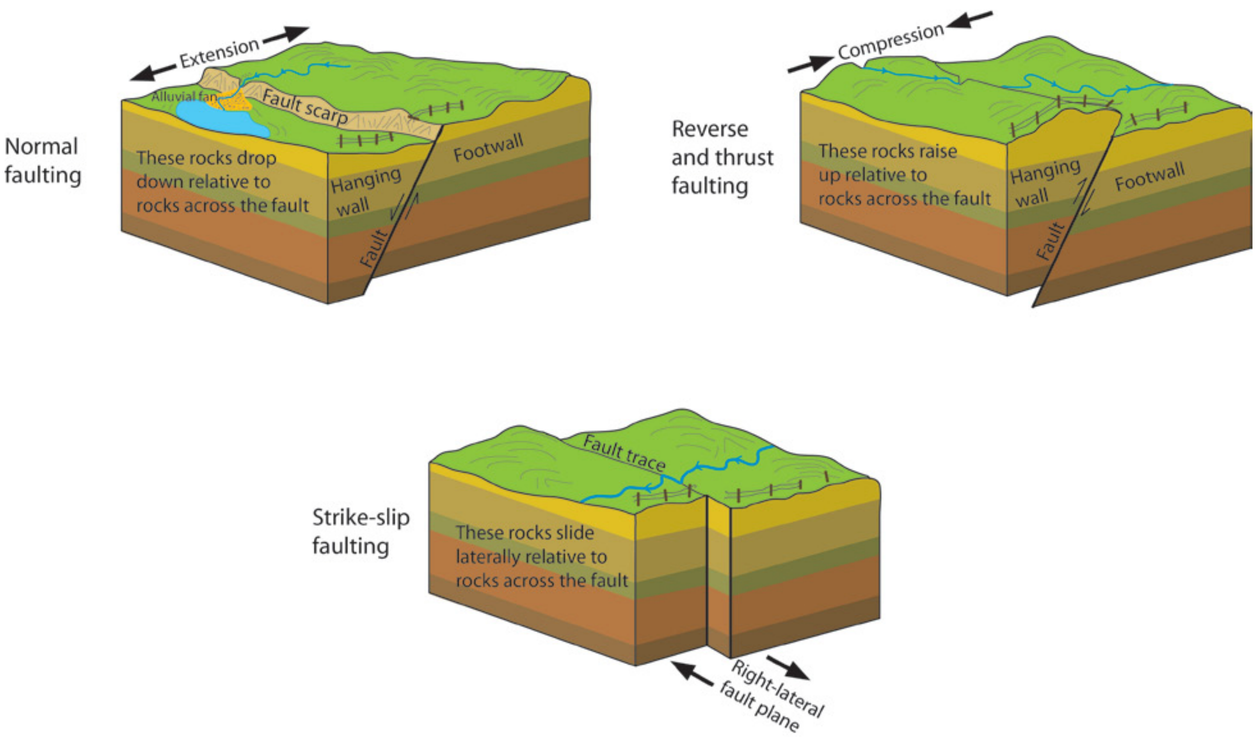


Figure 5. Schematic graphics illustrating different fault types present in southern Arizona. As a way of orientation, if you walked down a fault plane, your feet would be on the "footwall," and the rocks over your head would form the "hanging wall." In a normal fault the hanging wall moves down relative to the footwall. Normal faults result from extension (pulling apart) of the crust. In a reverse fault the hanging wall moves up relative to the foot wall. A thrust fault is similar to a reverse fault only the dip angle of a thrust fault is less than 45°. Reverse faults occur when the crust is compressed. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. If the movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. If movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

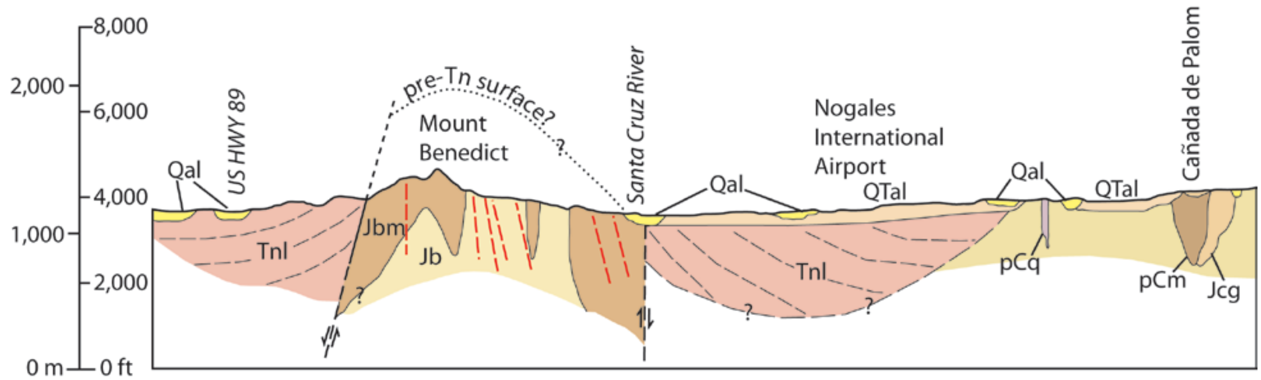


Figure 6. Geologic structural cross-section showing the Mount Benedict horst block and normal faults that separate the uplift from the Santa Cruz Valley to the west and the Santa Cruz River and Nogales International Airport to the east. This cross section is located approximately 500 m (1,500 ft) southwest of the Guevavi Unit. Normal faulting in the Basin and Range Province juxtaposed older Jurassic igneous rocks in the Mount Benedict horst (map units Jm and Jb) against younger Tertiary (Paleogene and Neogene) rocks in the basin (e.g., map unit Tnl). See fig. 7 and map unit properties table for more information about the geologic map units. Graphic by Trista Thornberry-Ehrlich (Colorado State University), after cross-section C-C′ in Simons (1974), which is included in the GIS data. 2x vertical exaggeration.

Era	Period	Tumacácori Mission Unit	Calabazas Mission Unit	Guevavi Mission Unit	General Description
Cenozoic	Quaternary	Alluvium, terrace, and floodplain deposits (Qycr, Qy, Qyr)			Sand, gravel, silt, clay.
			Alluvium and talus deposits (Qal)		Alluvium: gravel, sand, silt, clay. Nogales: volcanic conglomerate.
	Neogene		Nogales Formation (Tn)	Older alluvium (QTal)	
	Paleogene	Regional Unconformity			Rocks either removed by erosion or never deposited.
Mesozoic	Cretaceous		Salero Formation (Ks)		Feldspar-rich sandstone and pebbly sandstone.
		Regional Unconformity			Rocks either removed by erosion or never deposited.
	Jurassic			Quartz monzonite (Jb; Jbm)	Light- to brownish-gray, porphyritic quartz monzonite. Phenocrysts of plagioclase and potassium feldspar.

Figure 7. General stratigraphic column for Tumacácori National Historical Park illustrating relationships between units within or immediately adjacent to the park boundaries. An “unconformity” is a substantial break or gap in the stratigraphic succession. Geologic map unit symbols are in parentheses (see Map Unit Properties Table and Geologic Map Data section). Colors are U.S. Geological Survey standard timescale colors.

Figure 8. Pimería Alta. When Padre Kino and other Jesuit missionaries entered the lush river valleys of the Pimería Alta, they encountered O'odham communities already established along the riverbanks. National Park Service photograph available online: http://www.nps.gov/tuma/historyculture/pimeria-alta.htm, accessed March 29, 2010.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Tumacácori National Historical Park on April 4, 2006, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Two primary geologic issues were identified at the 2006 scoping session for Tumacácori National Historical Park included: 1) hazardous waste issues, and 2) groundwater and surface water quality.

In addition, flooding and debris flows (sediment-rich slurries) may erode the banks of the Santa Cruz River at all three units. Minor hazards that may present potential issues for park management include clays in unconsolidated sediments that swell with the addition of water and then shrink upon drying, seismic activity, and land subsidence.

Hazardous Waste Issues

When the National Park Service acquired additional land at the Tumacácori Mission Unit in 2002, the park also acquired four underground storage tanks, which presented a potential issue if they had been leaking. The tanks and ancillary equipment were removed and the soil tested for contamination. No contamination was detected, and the site was backfilled with clean soil, restored, and recorded as closed (Steve Gastellum, Facility Manager, Tumacácori NHP, written communication, March 30, 2010).

Surface Water Quality and Quantity

In 2006, surface water quality was a major issue at Tumacácori National Historical Park. Raw sewage and garbage flowed into the Santa Cruz River from Nogales Wash, north of Nogales, Arizona. This wash, concrete-lined farther south, enters the Santa Cruz River north of the Calabazas Mission Unit. Floods rampaged through Nogales Wash in 2006 and 2008, causing additional sediment and waste to flow into the river. The Nogales International Wastewater Treatment Plant (NIWTP), located at the confluence of Nogales Wash and the Santa Cruz River, did not meet U.S. Environmental Protection Agency (EPA) regulations.

Prior to a technology upgrade of the NIWTP in 2009, the Water Resources Division (WRD) of the National Park Service analyzed the results of surface-water-quality data collected from 101 monitoring stations in the upper Santa Cruz River Valley, from Tubac, Arizona, to the international border (National Park Service 2003). None of the monitoring stations was located within park boundaries, and most of the sites were upstream from the NIWTP. Most of the stations represented either one-time or intensive single-year sampling events. Concentrations of arsenic, barium, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, and zinc exceeded their respective EPA drinking water criteria, and all but nickel exceeded their respective acute freshwater criteria (National Park Service 2003).

Following the technology upgrade in 2009, the NIWTP now meets all required permit limits for the 57 million liters (15 million gallons) per day of wastewater it discharges to the Santa Cruz River (fig. 9) (Environmental Protection Agency 2009). Currently, the plant has the capacity to treat up to 65.1 million liters (17.2 million gallons) per day of sewage (International Boundary and Water Commission 2010). Approximately 80% of the waste comes from Mexico. Between 5 and 15% of Mexico's contribution could potentially be pumped back to the Los Alisos plant, which will be under construction in 2012 (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, August 25, 2011).

The upgrade to the NIWTP primarily affects the Tumacácori Mission Unit. The unit protects 1.6 km (1 mi) of rare southwest cottonwood-willow riparian environment, which is one of the most endangered ecosystems in the United States (National Park Service 2010a). This lush corridor of water-loving plants, growing along the banks of the Santa Cruz River, provides essential habitat for many plants, birds, and other animals that could not otherwise survive in the surrounding desert (figs. 8 and 10). The upgrade removed ammonia from the river and increased dissolved oxygen levels, which has led to increased fish and macroinvertebrate populations (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, May 26, 2010).

Without the effluent from the NIWTP, the Santa Cruz River would be an intermittent (ephemeral) stream, but this water source is not assured into the future. Prior to the treatment plant's construction, reliable water sources were found at locations where near-surface bedrock redirected groundwater toward the surface. Communities such as Tumacácori, Guevavi, and Tubac relied on these water sources for hundreds of years. For the Tumacácori Mission Unit, the effluent from the treatment plant offsets the negative impacts to the river's natural flow caused by such human activities as groundwater pumping, water diversion, livestock grazing, and land clearing and development (National Park Service 2007). However, due to groundwater pumping, the Santa Cruz River is completely dry at the Calabazas and Guevavi units except during flood events (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, May 25, 2010).

Although the NIWTP has been upgraded, heavy metal contamination and *Escherichia coli* (*E. coli*/fecal) bacteria remain significant issues for resource management. Possible anthropogenic sources for heavy metal contamination include industrial and municipal wastewater discharges, stormwater runoff, mining and quarrying operations, agricultural and ranching activities, leaking residential septic tanks, recreational use and atmospheric deposition (National Park Service 2003; Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, August 25, 2011). Erosion caused by flash floods may also contribute contaminants to surface water. Recently, excessive cadmium concentrations, which may originate from machine shops in Mexico, have been detected in the Santa Cruz River. In 2011, Cadmium was also found within the sludge removed from the treatment plant and used as fertilizer by local farmers (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, August 25, 2011). Because of continued contamination of the Santa Cruz River, the park recommends that visitors avoid all contact with the river water (National Park Service 2007).

The National Park Service's Sonoran Desert Inventory and Monitoring Network (SODN) plans to implement the following monitoring protocols for Tumacácori National Historical Park: climate, groundwater, land birds, and streams (National Park Service 2010b, 2010c). As part of these protocols, the SODN will monitor water chemistry and quality, channel morphology, and stream discharge. In addition, the U.S. Geological Survey and the National Park Service are conducting a joint study on the emerging contaminants in the area. Additional, detailed information regarding groundwater and surface water at Tumacácori National Historical Park may be obtained by contacting the Water Resources Division of the National Park Service, located in Fort Collins, Colorado. Visit the Sonoran Desert Network and Water Resources Division online: http://science.nature.nps.gov/im/units/sodn/ and http://www.nature.nps.gov/water/ (accessed August 25, 2011).

Flooding and Debris Flows

In the Tumacácori area, flood hazards consist primarily of overbank flooding and debris flows along the Santa Cruz channel and lateral erosion of unstable channel banks. Although the Santa Cruz River is entrenched up to several meters below the historical floodplain, its channel cannot contain large floods. One or two major floods occur each year in Tumacácori National Historical Park following any high precipitation event. Woody debris (and subsequent trash accumulations) commonly dam channels (fig. 11). As one recent example, extensive flooding occurred at the Tumacácori Mission Unit when 10 cm (4 in) of rain fell from January 22 to 23, 2010, in this area that averages 25 cm (10 in) of precipitation each year. This rainfall event caused significant damage to the church. River floods do not reach the church, however heavy rainfall directly impacts the structure (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, August 25, 2011).

Winter and late-summer-to-early-fall storms have caused the largest floods along the Santa Cruz River. For example, the Santa Cruz River gauge near Nogales, which normally records less than 142 cubic meters per second (cms) (5,000 cubic feet per second, or "cfs"), recorded a peak discharge of 878 cms (31,000 cfs) during October 1977 (Youberg and Helmick 2001). In October 1983, the Santa Cruz River gage near Continental, approximately 32 km (20 mi) north of the park, recorded a peak discharge of 1,274 cms (45,000 cfs).

The October 1983 flood was the largest flood to affect the Tucson area in the 20th century, and it caused significant damage. Every bridge except one that spanned the Santa Cruz River was either damaged or completely washed away (National Weather Service 2010). Nearly 18 cm (7 in) of rain fell in August and September, so that by October, the soil in the metro area was saturated. A surge of moisture from Tropical Storm Octave, located off the central Baja, California coast, caused torrential rains to drench the area over a four-day period. Bank erosion caused several buildings to collapse into Rillito Creek, and extensive damage occurred to agriculture in Marana.

Large floods in 2006 and 2008 did not significantly impact Tumacácori National Historical Park, although areas north and south of the park suffered considerable flood damage (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, May 26, 2010). Five weeks of rain in 2006 repeatedly flooded homes in Tumacácori and areas of Tubac and Amado (Vandervoet 2006). Trees left by previous debris flows blocked drainage culverts, and thick vegetation choked arroyos. Arroyos in this area are deeply incised, some up to 3 to 4 m (10 to 12 ft) deep. On July 27, between 8 to 14 cm (3 to 5.5 in) of rain fell in five minutes and flooded Interstate 19 in Tubac. This same storm caused debris flows in Coronado National Memorial, approximately 58 km (36 mi) east of the Guevavi Mission Unit, and Saguaro National Park, which lies on the eastern border of Tucson (Graham, 2011).

Arizona declared a state of emergency in Santa Cruz County following flooding of Nogales Wash in 2008. Flooding collapsed a 300-m (1,000-ft) tunnel and threatened to breach a buried sewage line that carries 53 million liters (14 million gallons) of untreated sewage into Arizona daily. Had the sewage line ruptured, the capacity of the Nogales International Wastewater Treatment Plant could have been surpassed, and the

Santa Cruz River could have received an unwelcome increase in sediment load and contaminants.

Since the 2008 flood, the International Boundary and Water Commission (IBWC) has initiated repair work on Nogales Wash. According to IBWC Commissioner C. W. Ruth in his stormwater planning presentation for the Nogales area, the tunnel will be repaired, retention basins and weirs constructed, a hydrologic study conducted, and a flood warning system installed (Ruth 2009).

During flood events, high flow velocities also cause severe lateral erosion of channel banks, in addition to overbank flooding. Modern alluvial sediments (map unit "Qycr"), and weakly consolidated floodplain and terrace deposits less than 10,000 years old (map unit "Qyr"), are especially prone to bank erosion in the park (Youberg and Helmick (2001).

Beyond the park boundaries, smaller tributaries that drain the mountain ranges and flow into the Santa Cruz River basin are susceptible to flash flooding. Flooding that occurs on alluvial fans with minimal topographic relief are typically not constrained by well-defined channels and tend to spread quickly across a wide area. Potential flood-prone areas in the vicinity of the Tumacácori Mission Unit include those areas mapped as Holocene (10,000 years ago to the present-day) alluvium (map units "Qy," "Qy1," and "Qy2") (Youberg and Helmick 2001).

Estimating flood frequency on the Santa Cruz River remains complicated because storms and floods are products of both local monsoonal conditions and climate variability in the tropical Pacific (Webb and Betancourt 1992). For example, monsoonal storms controlled flood frequency from 1930 to 1959. However, prior to 1930, and from 1960 to 1986, dissipating tropical cyclones generated during El Niño-Southern Oscillation conditions enhanced winter, spring, and fall precipitation in southern Arizona and influenced flood frequency.

Global climate change may add to the difficulty in predicting flood frequency along the Santa Cruz River. Projections of future climate change suggest that water supplies in the Southwest will become increasingly scarce. Landscapes and ecosystems will be transformed with an increase in temperatures, drought, wildfire, and invasive species. Increased groundwater pumping will lower water tables and rising temperatures will reduce river flows. Paradoxically, flooding may also increase due to more intense storm events, including more rain-on-snow events that lead to rapid runoff in areas where increased drought and fire have reduced vegetation cover (Karl et al. 2009).

Droughts are common in the Southwest. In the past 2,000 years, decades-long "megadroughts" have impacted the region, significantly reducing the flow of the Colorado River and the Sierra Nevada headwaters that are critical for California. Since 1999, Arizona has been part of the most severe western drought of the last 110 years (Karl et al. 2009; Arizona Department of Environmental Quality 2010).

By monitoring streams and groundwater at Tumacácori National Historical Park, the SODN will be able to assess changes to the ecosystem that might accompany climate change. Increased drought may initiate changes in sediment loads, water chemistry, flood magnitude and duration, riparian habitat, and macroinvertebrates. In addition, SODN monitoring will record fluctuations in groundwater quantity that may be due to a reduction in precipitation recharge (National Park Service 2010c). Recognition of any changes may help the Tumacácori resource manager address issues occurring within park boundaries.

Expansive Clays

Some of the surficial units in the Tumacácori National Historical Park region contain clay minerals that expand with the addition of water and shrink upon drying. Depending on the type and amount of shrink-swell clay, cracks may develop in foundations, walls, and roads. Early and Middle Pleistocene alluvial deposits (mapped as "Qo" and "Qm," respectively) contain shrink-swell clay that may present potential problems, but these units are not mapped within park boundaries (Youberg and Helmick 2001). The National Park Service Soil Resources Inventory provides detailed information regarding soil in the parks and may be accessed through http://science.nature.nps.gov/im/inventory/soils/index.cfm (accessed August 25, 2011). A soil survey geographic database (SSURGO) was completed for Tumacácori National Historical Park in 2006 (National Park Service 2006b)

Seismic Activity (Earthquakes)

Although some regions of the Basin and Range Province remain seismically active, including areas of northern Arizona, earthquakes in the area around Tumacácori National Historical Park, and Santa Cruz County, in general, are extremely rare (fig. 12). Quaternary fault zones in southeastern Arizona show very long recurrence intervals between surface ruptures (Pearthree and Calvo 1987). In the past century, 14 earthquakes have produced minor tremors within Arizona's borders, and most of these affected northern or north-central Arizona (U.S. Geological Survey Earthquake Hazards Program 2009). In the Santa Rita fault zone that extends northward from Tubac, late Pleistocene surficial units (map unit "Ql1") have been displaced, but latest Pleistocene (map unit "Ql2") and Holocene alluvium (map unit "Qy") have not been faulted. This field evidence brackets the youngest faulting between 10,000 and 130,000 years ago (Youberg and Helmick 2001).

While the Richter magnitude scale measures the seismic energy released by an earthquake, the Modified Mercalli intensity scale attempts to quantify the damage produced by an earthquake. The Modified Mercalli scale has 12 levels, with shaking being widely felt at level IV and significant damage beginning at level VII. The most recent earthquake to occur in the Nogales area occurred on March 30, 1916, and registered a level VI on the Modified Mercalli intensity scale (Arizona Earthquake Information Center 2009). At this level, heavy furniture may move and chimneys may be damaged, but overall damage is slight. According to the Arizona Earthquake Information Center (2009), all but the northeastern corner of Santa Cruz County lies within an area for potential earthquakes of intensity level VI.

Historically, the largest earthquake in Arizona occurred in 1959 when a magnitude 5.6 earthquake shook the Arizona-Utah border. The earthquake was classified as a level VI on the Modified Mercalli intensity scale. Ground shaking caused minor damage to chimneys and walls, broke windows, and knocked dishes from store shelves in Fredonia, Arizona. The shock also triggered a landslide at Mather Point in Grand Canyon National Park (U.S. Geological Survey 2009).

The most famous earthquake to shake southeastern Arizona occurred in 1887. The earthquake's epicenter was in Sonora, Mexico, approximately 306 km (190 mi) southeast of Tucson. Ground-shaking cracked buildings and destroyed chimneys throughout the sparsely populated region. Tremors set railroad cars in motion. The earthquake occurred in the San Bernardino Valley of northeastern Sonora, which forms part of a long, continuous rift valley that extends into the Basin and Range Province of Arizona (Sumner 1977; U.S. Geological Survey 2009). The earthquake had an estimated Richter magnitude of 7.2 (McGarvin 1987; DuBois and Smith 1980).

Information and research on Arizona earthquakes is collected and distributed by the Arizona Earthquake Information Center (AEIC), which is located in the geology building on the Northern Arizona University campus. Updated information is available on their website: http://www4.nau.edu/geology/aeic/index.html (accessed June 12, 2010). Information concerning earthquakes occurring around the globe may be found at the U. S. Geological Survey's Earthquake Hazards Program at http://earthquake.usgs.gov/ (accessed June 12, 2010).

Groundwater Depletion, Subsidence, and Earth Fissures

Groundwater is a valuable resource in the dry region of the southwestern United States, where surface water is relatively scarce. Many areas of the southwest, including central and south-central Arizona, are experiencing groundwater depletion, a term used to define long-term water-level declines due to sustained groundwater pumping. In south-central Arizona, groundwater pumping for irrigation, mining, and municipal use far exceeds groundwater recharge. In some localities, groundwater pumping is 500 times greater than groundwater recharge (Arizona Land Subsidence Group 2007). In parts of Tucson's well field, water levels had declined by more than 46 m (150 ft) between 1947 and 1981, and they continue to decline (Anderson 1988b). Along the Santa Cruz River south of Tucson, lowering the water table to support population growth has resulted in a loss of streamside vegetation (fig. 13) (U.S. Geological Survey 2010).

Land subsidence and associated earth fissures often accompany groundwater depletion. Although currently not an issue for Tumacácori National Historical Park, land subsidence and earth fissures create significant hazards in south-central Arizona. In unconsolidated sediments, groundwater occupies the pore space between the clasts, and the water pressure keeps the pore space open. If groundwater is removed from the pore space, the sediments collapse or compact into the opening. Compaction of sediments in near-surface aquifer systems due to groundwater pumping is the single largest cause of land subsidence (U.S. Geological Survey 2000). From 1987 to 1991, for example, the Tucson basin subsided at an average rate of 1 cm (0.4 in) per year. Near Eloy, Arizona, which is located between Phoenix and Tucson, the land has settled by as much as 4.5 m (15 ft) due to groundwater withdrawal. West of Phoenix, the land has subsided up to 5.5 m (18 ft) (Youberg and Helmick 2001).

Most fissures occur in Pinal and Maricopa counties, with the most severe fissures and land subsidence occurring in the area near Eloy (Gelt 1992). Fissures may reach 15 m (50 ft) deep and extend up to 13 km (8 mi) in length (Arizona Geological Survey 2006). They cause millions of dollars in property and infrastructure damage, including damage to roads, pipelines, canals, flood retention structures, bridges, and buildings. Fissures may also provide a conduit for contaminated surface water to rapidly enter groundwater aquifers (Arizona Land Subsidence Group 2007).

Due to differences in rates of groundwater pumping or subsurface compaction, fissures that often accompany excessive groundwater pumping originate as small cracks. These small cracks may grow quite large with subsequent water erosion. For example, within days of torrential monsoon rains in August 2005, water erosion transformed an earth fissure near Queen Creek, Arizona, southeast of Phoenix, into an open crevasse 1.5 to 3 m (5 to 10 ft) wide, 7.6 m (25 ft) deep and several meters in length (Arizona Geological Survey 2006). On February 14, 2010, the fissure reopened to a depth of approximately 6 m (20 ft) following heavy rainstorms (fig. 14) (Allison 2010).

Land subsidence has been occurring across Arizona since the 1940s, and earth fissures, which have become increasingly common since the 1950s, have been known in Arizona since 1927. Arizona leads all states in the number of known earth fissures caused by groundwater pumping (Gelt 1992). Growing public concern over earth fissures and the damage they cause inspired the Arizona legislature to initiate a comprehensive earth fissure mapping program in 2006 (Arizona Geological Survey 2006; Allison and Shipman 2007).

Most of the twenty-two study areas designated in Pinal, Maricopa, and Cochise Counties have been mapped, and the published maps are available through the Arizona Geological Survey Earth Fissure Viewer at http://services.azgs.gov/OnlineMaps/fissures.html (Michael Conway, Geologist, Arizona Geological Survey, written communication, March 6, 2011). This interactive viewer delivers recent maps of earth fissure locations throughout southeastern Arizona. Additional information and mapping updates may be obtained at Arizona's Earth Fissure Center website, maintained by the Arizona Geological Survey, available at http://www.azgs.state.az.us/EFC.shtml (accessed June 12, 2010).

Although earth fissures and land subsidence present significant issues for parts of Arizona, no fissures have been noted in the Tumacácori area of the Santa Cruz River Valley, and land subsidence appears to be quite modest (Michael Conway, Geologist, Arizona Geological Survey, written communication, March 7, 2011). However, if groundwater pumping increases in the vicinity of Tumacácori National Historical Park, the potential for land subsidence and earth fissures will also increase.

Figure 9. The upgraded Nogales International Wastewater Treatment Plant, upstream (south) of the Tumacácori Mission Unit, Arizona. The upgrade consisted of a Biological Nutrient Removal (BNR) system that removed nitrogen compounds in the discharged effluent, which were known to be detrimental to the fish and wildlife along the Santa Cruz River. International Boundary and Water Commission photograph available at http://www.ibwc.state.gov/Organization/Operations/Field_Offices/Nogales.html, accessed March 30, 2010.

Figure 10. Landscape surrounding Santa Cruz River and Tumacácori National Historical Park. Note the ribbon of relatively lush vegetation surrounding the Santa Cruz River snaking through the lower center of the image. The Santa Rita Mountains rise rapidly to the northeast. The Tumacácori Mission Unit lies along the Santa Cruz River just below center. National Park Service photograph courtesy Jeremy Moss (Tumacácori National Historical Park).

Figure 11. Woody debris and trash clogs the Santa Cruz River following a flood event. National Park Service photograph courtesy Jeremy Moss (Tumacácori National Historical Park).

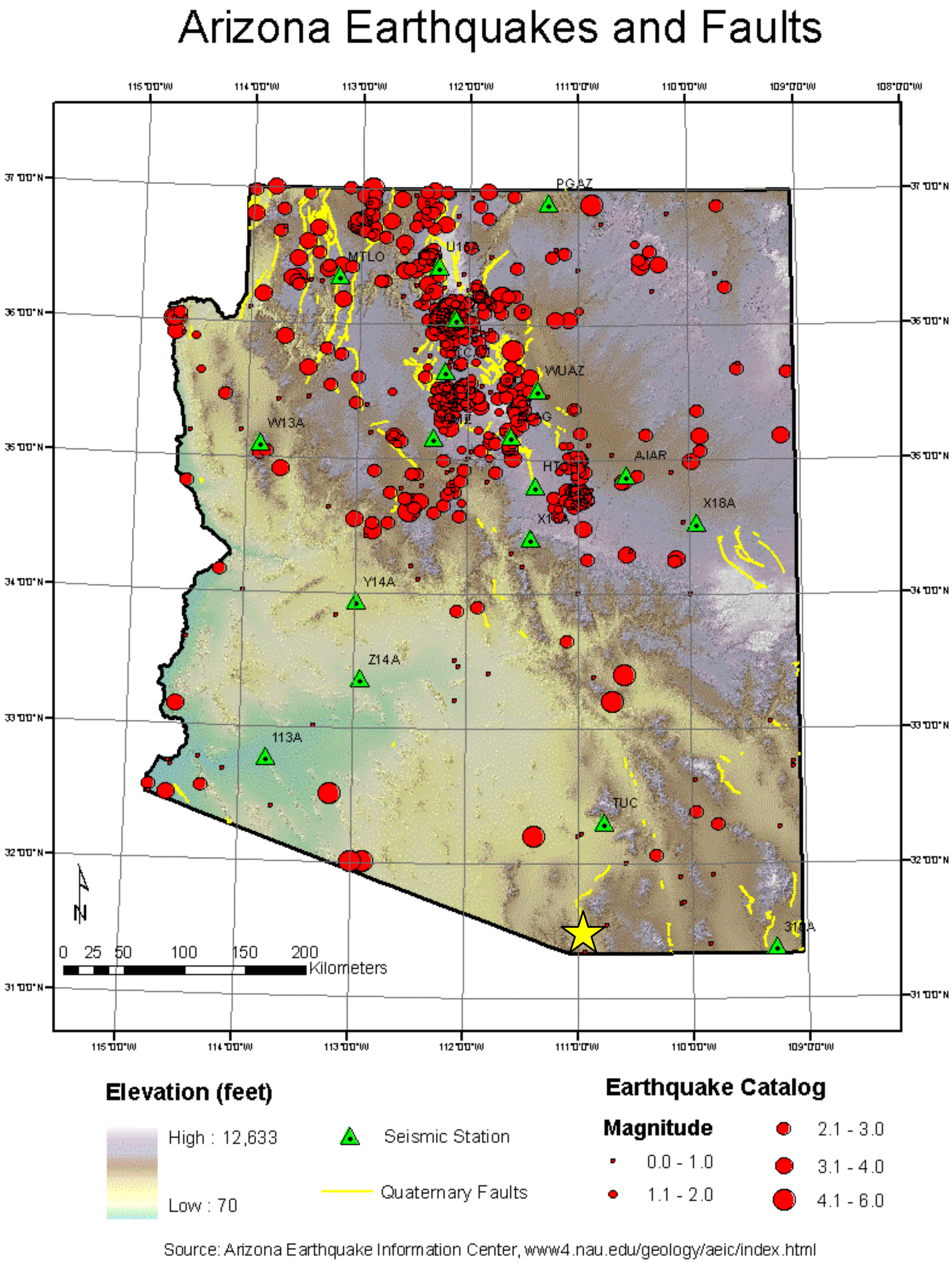


Figure 12. Map showing the location of historical earthquakes occurring within Arizona, as of January 18, 2010. The map also shows faults that have been active during the Quaternary (2.6 million years ago to present-day) although the most recent movement on the faults is not defined. Note that only two earthquakes, each with a magnitude of 0.0 to 1.0 on the Richter magnitude scale, have occurred in the vicinity of Tumacácori National Historical Park, represented by the yellow star (not to scale). Arizona Earthquake Information Center, graphic online: http://www4.nau.edu/geology/aeic/eq_fault_maps.html, accessed June 12, 2010.

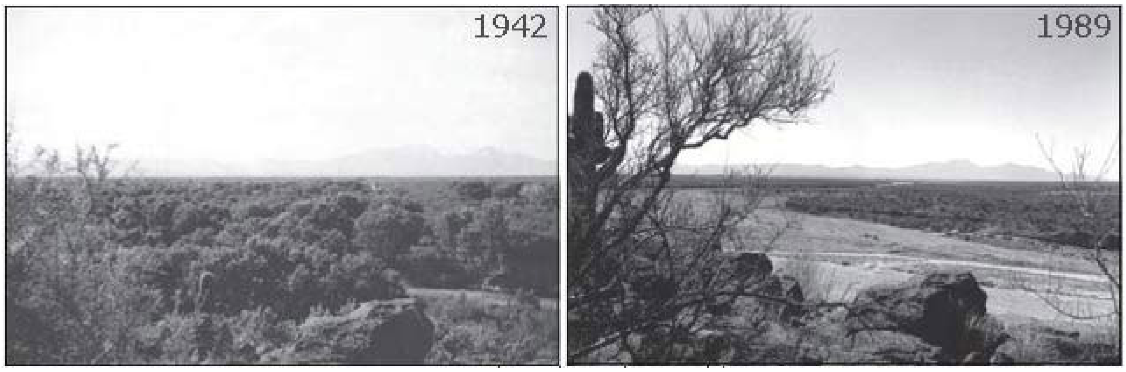


Figure 13. A lowered water table resulted in a loss of streamside vegetation along this reach of the Santa Cruz River south of Tucson, Arizona. In 1942, vegetation grows in the riparian (streamside) area of the river, indicating that water is accessible to plant roots. In 1989, however, riparian trees have largely disappeared from the site due to lowered groundwater levels. U.S. Geological Survey photograph by Robert Webb, available http://ga.water.usgs.gov/edu/gwdepletion.html, accessed July 1, 2010.

Figure 14. An earth fissure near Queen Creek, Arizona. This fissure opened in August 2005 and reopened in February 2010, as a result of heavy rainfall in January. The telephone pole is used to suspend water lines in the earth fissure. Photograph (in 2010) by and courtesy of Joe LaFortune (Town of Queen Creek).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Tumacácori National Historical Park.

Tumacácori National Historical Park was built on the margin of a historical floodplain. Deposits in the Tumacácori Mission Unit record a complex, recent geologic history involving flooding and erosion. In addition to fluvial deposits, the Calabazas and Guevavi units also contain Mesozoic sedimentary and igneous rocks that record geologic processes occurring between 200 million years ago and 65 million years ago.

At the scoping meeting in 2006, park managers expressed an interest in detailed mapping of the surficial deposits in order to better understand the distribution of current alluvial fans, debris flow deposits, and channel patterns. Maps of older, abandoned channels that lie within the present floodplain might also prove to be beneficial. Youberg and Helmick mapped the surficial deposits at Tumacácori Mission Unit in 2001, however more detailed mapping is desired by park staff. In 1974, Simons mapped the general surficial geology of the Calabazas and Guevavi Units, but detailed surficial maps of these units do not exist.

Fluvial Features

Modern river channel processes and features dominate the landscape at the Tumacácori Mission Unit. The configuration of today's channel began to form during the development of arroyos in the late 1800s. Erosion caused by large flood events during the 20th century caused catastrophic channel widening and entrenchment of the Santa Cruz River system south of Tucson. Significant floods on the Santa Cruz River occurred in 1890, 1905, 1915, 1968, 1974, 1977, 1978, 1983, 1993, 2006, 2008, and 2010 (Betancourt 1990; Youberg and Helmick 2001; Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, May 26, 2010).

A growing population in Tucson and southern Arizona in the late 19th century helped to exacerbate channel incision and arroyo formation. Tucson's population rose sharply in the 1880s, increasing the demand for potable water. The Southern Pacific Railroad entered Tucson in 1880, furthering its accessibility. Domestic, recreational, agricultural, and industrial water demands led to inadequate engineering of ditches, construction of reservoirs, development of springs, and water-control features; all this enhanced the probability that flooding would initiate new arroyos, and further entrench existing ones, in the Santa Cruz basin (Betancourt 1990).

Moderate to large flow events continue to easily erode the unconsolidated sand and gravel deposits in the arroyos and Santa Cruz River channel (map unit "Qycr"). Although some areas of the channel banks have been protected with soil cement (a mix of pulverized natural soil, Portland cement, and water), the general reaches of the Santa Cruz River in the Tumacácori area are unprotected and subject to lateral erosion during flood events (Youberg and Helmick 2001).

Cottonwoods, willows, and other water-loving vegetation crowd the lush corridor along the Santa Cruz River (figs. 8 and 10). The channel deposits of sand and gravel provide essential habitat for many plants and animals that could not otherwise survive in the surrounding desert (National Park Service 2010a).

Floodplains and terrace deposits that are less than 10,000 years old border the main channel of the Santa Cruz River (map unit "Qyr"). In the Santa Cruz Valley, agriculture and urban development have altered most of these surfaces. Arroyo cutting of the 1880s left most of the Holocene terraces isolated from today's active floodplain. However, if an arroyo is not deeply entrenched, large flood events may initiate unconfined flow across the relatively flat terrace surfaces (Youberg and Helmick 2001). The sand, silt, and clay of these floodplain and terrace deposits support a mixture of mesquite, hackberry, ash, and Mexican elderberry, along with acacia and palo verde trees, near the streamside corridor.

In the Tumacácori region, Pliocene to early Pleistocene alluvium that filled the basin between 5 and 1 million years ago (map unit "QTs") and middle Pleistocene (approximately 750,000 to 130,000 years ago) alluvium (map unit "Qm") dominate the landscape. The deeply-dissected and highly-eroded Pliocene to early Pleistocene alluvium form alternating ridges and deep valleys. Ridge crests are often 10 to 30 m (30 to 100 ft) above adjacent active tributary channels. These older alluvial fan deposits primarily consist of boulders, cobbles, and gravels (Youberg and Helmick 2001).

Moderate to deeply-incised tributary channel networks drain middle Pleistocene (approximately 750,000 to 130,000 years ago) alluvial surfaces. Middle Pleistocene alluvial fans and terraces display a distinctive dark red color, due to iron oxidation of the surface clasts and soil (fig. 15). The Pleistocene alluvial deposits support grasses with scattered cacti, mesquite, acacia, and ocotillo (Youberg and Helmick 2001).

Sedimentary Rock Features

Exposures of Mesozoic sedimentary rocks in the Calabazas Mission Unit consist of the Late Cretaceous (100 to 65 million years ago) Salero Formation (map unit "Ks") (Simons 1974). South of the old town site of Calabasas, the gray epiclastic (clasts derived from fragments weathered from pre-existing rocks) volcanic conglomerate may contain unusually large clasts up to 0.3 m (1 ft) in diameter. As much as 610 m (2,000 ft) of Salero Formation is exposed in the surrounding area.

The abundant plagioclase and potassium feldspars, which rapidly deteriorate (in terms of geologic time) at Earth's surface, suggest that the original sediments did not travel very far from their point of origin before they were buried and lithified into Salero Formation sandstone. One environment that may contain abundant feldspar-rich sediments is an alluvial fan, which typically forms at the base of a mountain range. Basins that formed in the Late Cretaceous were flanked by alluvial fan depositional environments similar to the basins in today's Basin and Range Province.

Volcanic conglomerate of the Neogene Nogales Formation (map unit "Tn") form the Cuates Buttes, immediately north of the Calabazas Mission Unit (Simons 1974). Named for exposures east and north of Nogales, Arizona, the Nogales Formation contains volcanic clasts eroded from the volcanic rocks of the Grosvenor Hills, along with abundant beds of sandstone and grit. Thin basalt flows that separate middle and upper members of the formation have been dated at 12.6 million years ago (Miocene epoch). In the surrounding area, the Nogales Formation has been subdivided into a 610-m (2,000-ft) thick Upper Member of epiclastic volcanic conglomerate and a 1,500-m (5,000-ft) thick Lower Member of conglomerate, fanglomerate, sandstone, and tuff (Simons 1974).

Igneous Rock Features

Quartz monzonite, a quartz- and feldspar-rich intrusive igneous rock, surrounds the southern and southwestern border of the Guevavi Mission Unit and forms Mount Benedict (map unit "Jbm") (Simons 1974). Radiometric ages suggest the rock crystallized approximately 164 to 160 million years ago, during the Jurassic period. In addition to quartz and feldspar, the quartz monzonite contains minor amounts of the minerals biotite, hornblende, and sphene. North- to northwesterly-trending igneous dikes intrude into the quartz monzonite (see "Overview of Digital Geologic Data" graphic). The rocks represent a time of intensive volcanic and magmatic activity in southeastern Arizona (see the "Geologic History" section).

Basin and Range Faults

The basin-bounding, normal fault (fig. 5) that separates the Santa Cruz graben from the Tumacácori Mountains lies approximately midway between the Tumacácori Mission Unit and the mountain front. A similar basin-bounding fault forms the eastern border of the Santa Cruz graben, and separates the graben from the San Cayetano Mountains, east of the Tumacácori Mission, and Mount Benedict (fig. 6; Drewes 1980). Quaternary and Tertiary (an older age designation that has been divided into the Neogene and Paleogene) alluvial fan and terrace deposits currently cover the surface trace of both faults.

The Santa Cruz River adjacent to the Calabazas Mission Unit and Guevavi Mission Unit flows in a valley created by a northwest-to-southeast trending normal fault (see "Overview of Digital Geologic Data" graphic). Mount Benedict forms a horst uplifted between this fault and a major north-to-south trending normal fault that parallels the Santa Cruz graben's basin-bounding fault (fig. 6). The north-south fault defines the western border of the Mount Benedict horst and offsets the fault that forms the Santa Cruz River valley, suggesting that it is younger than the northwest-to-southeast trending fault that forms the eastern border of the horst. North of the Santa Cruz River valley and southeast of the Calabazas Mission Unit, the north-south fault terminates into a number of less extensive normal faults that separate the Cretaceous Salero Formation from the Miocene Nogales Formation (Simons 1974; Drewes 1980).

Faulting in the Basin and Range Province brought older rock units, such as the Salero Formation, to the surface. Salero Formation strata have not only been uplifted but also tilted from 15° to 35° to the west. Tilting probably is due to Basin and Range Province faulting, but some tilting may also have occurred during the Cretaceous-to-Tertiary Laramide Orogeny (mountain-building event) that preceded Basin and Range extension.

Since the Nogales Formation was deposited after the Laramide Orogeny, the minor anticlines (convex-up, "A"-shaped folds) and synclines (concave-up, "U"-shaped folds) mapped within this unit by Drewes (1980) probably resulted from Basin and Range Province deformation. Most of these minor folds are exposed in the Nogales Formation between the Guevavi Mission Unit and the international border. Few folds have been mapped in the Cuates Buttes area, north of the Calabazas Mission Unit.

Basin-and-Range Landscape Features

The Basin and Range Province is a unique geological province found nowhere on Earth except in the southwestern United States (fig. 3). In the late 19th century, the famous geologist and U.S. Army officer, Major Clarence Edward Dutton, described the mountains of the Basin and Range as "an army of caterpillars crawling northward out of Mexico" (fig. 3) (qtd. in Short 2010). Aerial imagery reinforces Dutton's initial impression of the Basin and Range by contrasting the province's flat valley floors and parallel mountain ranges (fig. 3).

The basin-and-range landscape began forming approximately 15 million years ago in the Miocene. An area of high heat flow, centered beneath present-day Nevada, caused uplift of the Earth's crust and corresponding tensional stresses, which pulled apart the crust. Extension resulted in block faulting and the relative parallelism of the north-to-south trending mountain ranges and regularly-spaced grabens (fig. 3). Present elevation differences between the mountain ranges and valley floors can be as much as 900 to 1,520 m (3,000 to 5,000 ft) (Short 2010). Rising abruptly from the basin floor along the basin-bounding faults, the mountain ranges present an imposing topography (figs. 10 and 16).

Paleontological Resources

Quaternary vertebrate fossils, Pleistocene tortoise and mammoth remains, and fossils of beavers, camelids, and equids have been discovered at sites well removed from Tumacácori National Historical Park, but no fossils have been found within the borders of the park. There are four marine fossils within the park's museum collections, housed at the NPS Western Archeological Conservation Center. Given the paucity of fossiliferous formations in the Tumacácori area, and the lack of marine rocks, the specimens were probably all brought from elsewhere (Tweet et al. 2008). Cultural sites within the park, however, may contain fossils (Tweet et al. 2008). While they would not represent the original environment of deposition, these fossils might provide information regarding both the environment of southern Arizona at the time the animals lived, and how they were used in a more recent cultural context.

Cultural Features and Geologic Connections

Geology played a significant role during the Spanish mission-building period of southern Arizona. Under the direction of the resident or visiting priest, Indians constructed the mission buildings using local materials. Mesquite and pine trees provided roof beams, lintels, doors, furniture, and shutters. Roofs were also made from saguaro cactus ribs, as well as canes from ocotillo. Geologic units throughout the area provided the sand and clay to make adobe bricks and the thin, hard adobe plaster that coated the walls of the mission buildings (see cover, figs. 2 and 17). The walls of the missions were covered with a "lime plaster." The lime appears to have originated within the foothills and drainages on the west side of the Santa Rita mountains, perhaps from the Montosa Canyon and associated drainage. It was processed in a lime kiln on site. (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, August 25, 2011).

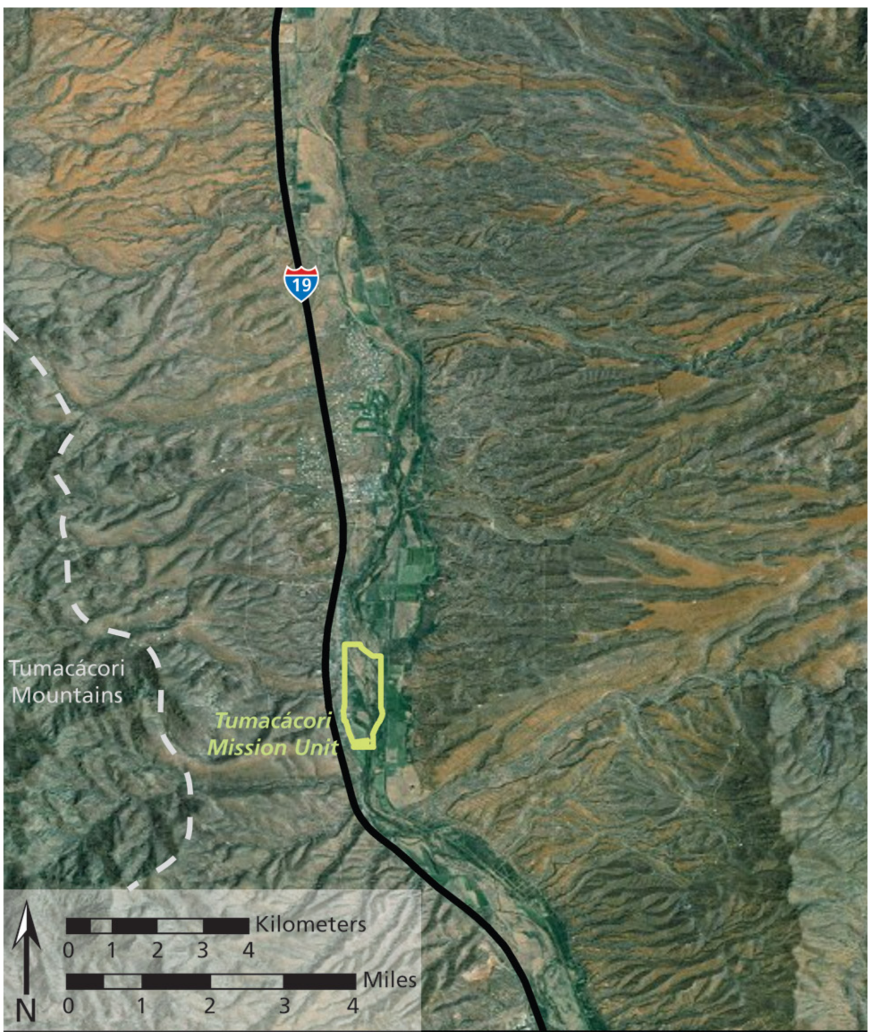


Figure 15. Aerial image illustrating the distinctive orange-red coloring of alluvium and terrace deposits, and their associated soils, surrounding Tumacácori Mission Unit (map units Qy2, Ql, Qlr, Qm, and Qmr on the Map Unit Properties Table). Weathering of iron-bearing minerals associated with clay-rich soils is responsible for the coloring. Older deposits tend to be redder. Compiled by Jason Kenworthy (NPS Geologic Resources Division) from ESRI Arc Image Service; USA Prime Imagery.

Figure 16. Northeast of the Tumacácori Mission Unit, the Santa Rita Mountains rise abruptly from the Santa Cruz Valley. National Park Service photograph by Tom Brennan, available at http://www.nps.gov/tuma/planyourvisit/attractions-around-tumacacori.htm, accessed July 2, 2010.

Figure 17. The Mission Church in the Tumacácori Mission Unit, Tumacácori National Historical Park, Arizona. Local sand and clay were used to make the adobe bricks for the mission buildings. Limestone, perhaps from the Santa Ritas, was used for the plaster. It was processed in a lime kiln on site (Jeremy Moss, Chief of Resource Management and Archaeologist, Tumacácori NHP, written communication, August 25, 2011). National Park Service Historic Photograph Collection photograph by George A. Grant (ca. 1947). The uniformed woman standing in the doorway is Sally (Brewer) Harris. According to the National Park Service, this photograph is the earliest known color image of a woman in an NPS uniform. Photograph available online: http://home.nps.gov/applications/hafe/hfc/npsphoto4h.cfm?Catalog_No=hpc%2D001370, accessed April 1, 2010.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Tumacácori National Historical Park, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The rocks in the Tumacácori area record only a brief portion of Earth's geologic past. Unconsolidated sediments represent deposition occurring since approximately 5.3 million years ago to the present (Pliocene to Holocene epochs) (fig. 18). Rocks in the Calabazas Mission and Guevavi Mission Units extend the geologic clock back to the upper Middle Jurassic (164.7 to 145.5 million years ago). However, the oldest rock in southeastern Arizona is the Pinal Schist, which formed about 1.65 billion years ago during Precambrian time.

Precambrian (prior to 542 million years ago)

When sediments that would form the Pinal Schist were deposited, the southern shoreline of proto-North America (the ancient core of what is now North America) transected what is now central Arizona, and turbidity currents deposited mud and silt into a marine basin forming offshore. Northwest-directed thrust faulting and folding compressed the basin sediments and attached them to the proto-North American continent (Conway and Silver 1989; Hoffman 1989). Regional metamorphism transformed the sediments into the Pinal Schist. Excellent exposures of Pinal Schist can be found in the Rincon Mountains of Saguaro National Park, east of Tucson, Arizona (Graham 2010).

By 1.4 billion years ago, most of what is now the Arizona land surface had been added to the proto-North American continent. New masses of molten rock then intruded the newly accreted coastal province. The granitic rocks in Fort Bowie National Historic Site, for example, intruded the Pinal Schist about 1.375 billion years ago (Drewes 1981; Graham in prep.).

The next 800 million years of the geologic history of southeastern Arizona remain a mystery. Erosion has removed any rocks that were deposited during this time, leaving a gap in the stratigraphic record (called an "unconformity") that separates the roughly 1.4-billion-year-old Precambrian rocks from the 542- to 510-million-year-old Cambrian rocks.

Paleozoic Era (542 to 251 million years ago)

Cambrian rocks initiate the Paleozoic era and record a major oceanic incursion onto the proto-North American continent about 520 million years ago. Throughout most of the Paleozoic, southeastern Arizona was covered by an ancient sea. Thick layers of carbonate and siliceous sediments accumulated on the sea floor.

Near the end of the Paleozoic, about 275 million years ago, a marine transgression flooded the western margin of North America, and marine carbonate environments rimmed the borders of Arizona (fig. 19). Subduction of the oceanic plate beneath the proto-North American continent caused west-to-east thrusting and the addition of continental shelf and slope rocks to the western margin. The South American tectonic plate collided with the proto-North American plate and closed the proto-Gulf of Mexico. The collision caused the uplift of the northwest-southeast-trending Ancestral Rocky Mountains in Colorado, the northeast-southwest-trending Sedona Arch in central Arizona, and the Mogollon Rim, an uplift in east-central Arizona. South of the Mogollon Rim, an offshore carbonate shelf developed in southeastern Arizona (Blakey 1980; Peterson 1980).

The most severe mass extinction event in the last 542 million years occurred at the close of the Permian. Up to 96% of marine species and 70% of terrestrial vertebrates may have perished. The only known mass extinction of insects occurred at this time. The loss of biodiversity is recorded in the extinction of 57% of all families and 83% of all genera. Thousands of species of insects, reptiles, and amphibians died on land while in the oceans, rugose corals and the once prolific trilobites vanished, as did many species of snails, urchins, sea lilies (crinoids), and some fish. Five million years later, at the dawn of the Mesozoic, the oceans began to evolve into the chemistry of the modern oceans, and on land, the first mammals and dinosaurs emerged.

Mesozoic Era (251 to 65.5 million years ago)

From the middle of the Paleozoic through the Mesozoic, the western margin of North America was an active plate margin where dense, oceanic crust subducted beneath lighter continental crust. An arcuate-shaped "magmatic arc" (also called a "volcanic arc") commonly forms above a plate-tectonic subduction zone (Fig. 20A). Plate convergence generates magma primarily from melting in the asthenosphere above the downgoing plate. Magma rises to form plutons and active volcanoes. During the Mesozoic, a magmatic arc formed along the western margin of North America (Oldow et al. 1989; Christiansen et al. 1994; Dubiel 1994; Lawton 1994; Peterson 1994). Magma chambers developed, and these igneous intrusions solidified to form plutons and batholiths, such as those exposed in Yosemite National Park, California.

Triassic Period (251 to 200 million years ago)

While thick sections of Triassic rock can be found in southern Arizona, no Triassic rocks exist in Tumacácori National Historical Park. By the Early Triassic, all the major land masses had merged together to form a single supercontinent called Pangaea, which was located symmetrically about the equator (Dubiel 1994). Pangaea reached its greatest size in the Triassic, and then began to split apart.

In the southwestern United States, a northwest-flowing river system developed, which included north-flowing tributaries in southern Arizona (Dubiel 1994). The Late Triassic was an unusually wet episode for the western interior of North America, and principal depositional environments included fluvial, floodplain, marsh, and lake settings, with minor eolian and playa environments forming at the close of the Triassic.

Jurassic Period (200 to 145 million years ago)

Dramatic modifications to the western margin of North America occurred in the Jurassic. The thick sequence of Late Triassic and Jurassic continental volcanic rocks in southeastern Arizona represents a major change from the shallow marine shelf conditions that persisted in the region during most of Paleozoic time (Kluth 1983; Dubiel 1994; Peterson 1994). Subduction of the oceanic plate beneath the overriding North American plate created a northwest-trending magmatic arc along the southwestern margin of North America (Tosdal et al. 1989).

In the Early Jurassic, voluminous pyroclastic rocks and volcanic flows erupted across most of the Sonoran Desert region of Arizona. Locally, crustal extension occurred within the volcanic arc. Quartz-rich eolian sand blew into the region from extensive dune fields located on the southern Colorado Plateau (Bilodeau et al. 1987; Tosdal et al. 1989). For approximately 35 million years, into the Middle and perhaps early Late Jurassic time, explosive volcanism continued to dramatically modify the southern Arizona landscape.

In the Middle Jurassic, Wrangellia, a collection of islands in the Pacific, collided with North America, causing volcanic activity along the west coast from Mexico to Canada (fig. 21). The collision caused west-to-east directed thrust faulting in Nevada and the northern encroachment of a shallow sea into Utah.

About 165 million years ago (Middle Jurassic), catastrophic volcanic eruptions occurred in southeastern Arizona, producing bowl-shaped depressions called calderas. Calderas form when overlying rocks collapse into an emptied magma chamber. Calderas in the southern Huachuca and Dragoon Mountains, east Tumacácori National Historical Park, record this violent volcanic activity. Coronado National Memorial, for example, lies within the Montezuma caldera, estimated to be 16 to 18 km (10 to 11 mi) in diameter (Lipman and Hagstrum 1992; Graham 2011).

Magma chambers that solidified in the subsurface produced granitic intrusions with a variety of textural and mineral compositions. The quartz monzonite of Mount Benedict (map symbols “Jb” and “Jbm”), adjacent to the Guevavi Mission Unit, formed at this time, as did the Jurassic granite in the Patagonia Mountains, the mountain range immediately east of the Guevavi Mission Unit (Drewes 1980). Abundant northwest-trending dikes (map symbols “r” “a” and “dike”) intrude the quartz monzonite, and so are younger igneous bodies (Simons 1974).

By mid-Late Jurassic time, strike-slip faulting related to the opening of the Gulf of Mexico generated large-scale, high-angle, primarily northwest-trending faults in southern Arizona (Tosdal et al. 1989). A large, northwest-southeast trending strike-slip fault zone, called the ‘Mojave-Sonora megashear,’ truncated and displaced approximately 800 to 1,000 km (500 to 600 mi) of the southwestern continental margin of North America. Regional extension stretched the crust of southeastern Arizona (Kluth 1983; Stevens et al. 2005; Anderson and Silver 2005; Haenggi and Muehlberger 2005).

At the end of the Jurassic, magmatism waned and finally ended. Rift (pull-apart) tectonics formed the Bisbee trough that extended into southeastern Arizona from the Gulf of Mexico. Alluvial-fan and fluvial deposits of the Bisbee Group (Glance Conglomerate) accumulated in the depression (Tosdal et al. 1989; Elder and Kirkland 1994; Dickinson and Lawton 2001; Haenggi and Muehlberger 2005).

Cretaceous Period (245 to 65.5 million years ago)

During the Early Cretaceous in southern Arizona, rifting along the northwest-southeast-trending Bisbee basin dominated the tectonic regime. Rather than accreting land to the continent as earlier tectonic events, Cretaceous tectonic forces were pulling the land apart. Rifting associated with the Mojave-Sonora megashear opened a series of local pull-apart basins (Elder and Kirkland 1994; Anderson and Nourse 2005).

Approximately 90 million years ago, early in the Late Cretaceous, oceanic-continental plate convergence along the western margin of North America caused sedimentary strata to be folded and thrust eastward over Precambrian basement rocks during the Sevier Orogeny (mountain-building episode) (fig. 20A). The rising mountains in the fold-and-thrust belt extended from Canada to Mexico. Sediment eroded from the mountains was deposited in an adjacent basin (“foreland basin”).

The Gulf of Mexico continued to rift open in the south, and seawater encroached northward into the subsiding basin. Marine water also began to transgress southward from the Arctic region. The seas advanced and retreated many times during the Cretaceous until a seaway extended from today’s Gulf of Mexico to the Arctic Ocean, a distance of about 5,000 km (3,000 mi) (Kauffman 1977). Southeastern Arizona formed part of the western border of this Western Interior Seaway, the most extensive interior seaway ever recorded in North America (fig. 22).

With the advent of the Laramide Orogeny, approximately 75 million years ago, the Western Interior Seaway began to retreat. Unlike the steeper angle of subduction thought to be responsible for the thrust faulting of the Sevier Orogeny, the subducting slab during the Laramide Orogeny was relatively flat (fig. 20B). Because flat-slab subduction transferred the compressive stress farther inland, the Laramide Orogeny involved deep-seated basement blocks of Precambrian rocks. Reverse and thrust faults transported these Precambrian units to the surface, where they are now exposed in the Rocky Mountains.

At the close of the Mesozoic era, about 65 million years ago, another burst of volcanic activity and faulting in southeastern Arizona resulted from the Laramide Orogeny. The Laramide Orogeny, which lasted from roughly 75 to 35 million years ago, is not only responsible for the modern Rocky Mountains, but is also responsible for most of the ores of copper, silver, and gold deposited in the southwestern United States (Pallister et al. 1997).

In southern Arizona, non-marine strata of the Salero Formation, mapped in the Calabazas Mission Unit (map symbol "Ks"), were derived from Jurassic granitic rocks and Triassic-Jurassic volcanic rocks similar to those exposed in the Patagonia Mountains. Composed primarily of conglomeratic alluvial-fan and possibly braided-stream deposits, the formation contains feldspar-rich and pebbly sandstones and minor volcanic tuff (Simons 1974). In latest Cretaceous and earliest Tertiary time, the entire area experienced uplift, tilting to the north, and erosion.

Cenozoic Era (the past 65.5 million years)

Paleogene and Neogene Periods (together called the "Tertiary": 65.5 to 2.6 million years ago)

Two processes dominated the tectonic evolution and sedimentation of Arizona in the Tertiary. The first was a resurgence of magmatism after a 10-to-30-million year quiescence. The second process involved lithospheric extension that gave rise to the current basin-and-range topography (Spencer and Reynolds 1989). Both processes were related to the evolving plate-tectonic setting of the continental margin of western North America. In the Tertiary, the angle of subduction steepened, and as the angle of subduction increased along the western margin, the Laramide Orogeny came to a close. The compressive forces decreased in the interior of western North America, and because the crust was no longer constrained, it began to relax. As it relaxed, extensional faults (normal faults) developed.

Beginning in the Paleogene and ending in the early Miocene, multiple intrusions of molten material occurred in southern Arizona. Near Tucson, Arizona, the Santa Catalina Mountains contain at least 12 plutons that can be divided into three intrusive episodes: 1) 75-to-60 million years ago (Latest Cretaceous to Paleocene), 2) 50-to-44 million years ago (Eocene), and 3) 29-to-25 million years ago (Oligocene) (Anderson 1988a). Paleocene andesitic to rhyolitic lava and tuff and volcaniclastic conglomerate unconformably overlie the Salero Formation (Simons 1974).

Lavas and low-volume tuffs erupted from a series of volcanic vents in southeastern Arizona from 45-to-40 million years ago (during the second intrusive episode) (Dickinson 1979; Nations et al. 1985; Kring 2002). A large number of volcanic calderas erupted in southern Arizona and New Mexico. Perhaps the best known is the Oligocene Turkey Creek Caldera, responsible for most of the volcanic rocks in Chiricahua National Monument. This caldera is about 20 km (12 mi) in diameter (Drewes 1982; Kring 2002; Graham 2009).

The lava flows, welded tuff, and pyroclastic rocks found in the Tumacácori Mountains and Grosvenor Hills resulted from volcanic activity during the third intrusive episode (Oligocene epoch) (Drewes 1980). Along the west flank of the Patagonia Mountains and the south flank of the Grosvenor Hills, uplift and erosion of these volcanic rocks produced the epiclastic volcanic conglomerate of the Miocene Nogales Formation, mapped near the Calabazas Mission Unit (map symbol "Tn") (Simons 1974).

By the early Miocene (23.03 to 15.97 million years ago), the divergent plate boundary (spreading ridge), that separated the Pacific plate from the Farallon plate, intersected the western margin of the North American plate (fig. 23). The collision of the divergent boundary with the active margin terminated subduction along this segment of the coast and activated the San Andreas strike-slip fault. The San Andreas Fault is more than 1,000 km (620 mi) long, with a cumulative right-lateral movement (fig. 5) of greater than 320 km (200 mi) (Oldow et al. 1989).

The change from subduction to strike-slip movement removed support for the thick crust in the Great Basin. Beginning about 15- to 10-million years ago (Miocene epoch), lithospheric extension collapsed the crust beneath the Great Basin. Crustal thinning produced tensional (pull-apart) faults in the eastern Sierra Nevada and Basin and Range Province, and the crust broke into blocks separated by new, more steeply dipping faults (fig. 4). Some blocks were displaced by as much as 1.4 km (2.4 mi) relative to other blocks, forming deep grabens ("basins") that presently contain thousands of meters of sediment eroded from adjacent mountain ranges.

Tumacácori Mission Unit lies within the Santa Cruz graben, which is bounded by Basin and Range basin-bounding faults. Normal faults that uplifted Mount Benedict, and juxtaposed the Cretaceous Salero Formation against the Tertiary Nogales Formation near the Calabazas Mission Unit, probably are the result of Basin and Range faulting, as well (fig. 6; Simons 1974; Drewes 1980). Minor folding in the Miocene Nogales

Formation, south of Mount Benedict, may also be the result of Basin and Range deformation. Subsequent erosion following uplift has exposed these older rocks at the surface.

Some of the normal faults in the province dipped gently beneath Earth's surface, forming detachment (décollement) faults. Regions initially close together were transported 10 to 25 km (6 to 15 mi) apart along these detachment surfaces. As the mass of the overlying rock was removed during fault movement, the part of Earth's crust beneath the detachment surfaces began to rise.

The rocks beneath the detachment faults that slowly rose to the surface were composed primarily of metamorphic rocks that formed under unusually high temperatures and pressures. Exhumed at the surface, these rocks formed domed-shaped mountain ranges called "metamorphic core complexes," a geologic feature first described in western North America. The Rincon Mountain District of Saguaro National Park forms part of a metamorphic core complex that includes the Tortilita Mountains, Santa Catalina Mountains, and Rincon Mountains (Coney 1979; Davis 1987; Spencer and Reynolds 1989; Dickinson 1991; Graham 2010).

Quaternary Period (the past 2.6 million years)

Tectonic activity in the Basin and Range began to wane in the Pliocene epoch and continued to diminish into the Quaternary (Menges and Pearthree 1989). The last episode of Basin and Range deformation in the Sonoran Desert ended between 10.5 and 6 million years ago, and it was only a minor influence in most areas of the Mexican Highland section of the Basin and Range Province during the Quaternary (fig. 3). Mountain ranges in the Sonoran Desert region are more worn down and worn back from the basin-margin faults than in the Mexican Highland section. Intermontane basins are typically wider than bordering mountain ranges (Morrison 1991).

During the Pleistocene, through-flowing streams dissected the basins. Stream dissection, however, was not continuous throughout the Quaternary. Rather, episodes of downcutting were followed by episodes of predominately lateral incision. This process resulted in a stepped series of stream terraces that are typically covered with several meters of alluvial gravel (Morrison 1991).

The oldest basin fill deposits in the upper Santa Cruz Valley consist of Pliocene to early Pleistocene alluvial fans dated from 5 to approximately 1 million years ago (map symbol "QTs") (Youberg and Helmick 2001). Deeply incised by tributary channel networks, these fans form a landscape of alternating eroded ridges and dissected valleys. Ridge crests typically rise 10 to 30 m (33 to 100 ft) above the adjacent active channels. The deposits of boulders, cobbles, and gravels derived from the nearby mountains vary from a few meters thick near the mountains to 260 m (850 ft) thick near Amado, Arizona. Lenses of sand, silt and clay interlayer with the coarser material (Youberg and Helmick 2001).

Early Pleistocene (approximately 2 million years to 750,000 years ago) alluvial fan remnants overlie the highly-dissected basin fill deposits. The deposits of cobbles, boulders, and sand are moderately to well-preserved on the upper piedmont surface near the Tumacácori Mountain front (map symbol "Qo"). These early Pleistocene surfaces record deposition (aggradation) at the highest levels of flow of the Santa Cruz River (Youberg and Helmick 2001).

Well developed, moderately-to-deeply incised tributary channel networks drain these Middle Pleistocene surfaces (map symbols "Qm" and "Qmr"). The eroded, rounded surfaces are composed of scattered pebbles and cobbles, and a strong soil development. Scattered river terrace remnants on the west side of the Santa Cruz River are typically 45 to 50 m (14 to 15 ft) above the modern river channel (Youberg and Helmick 2001).

During the late Pleistocene (approximately 130,000 to 10,000 years ago), alluvial fans and river terraces developed on the upper, middle, and lower piedmont (map symbols "Ql," "Qlr," and "Qlyr"). Active tributary channels have incised the surfaces up to 2 m (7 ft). Incision typically increases toward the mountain front and toward the southern end of the Santa Cruz Valley (Youberg and Helmick 2001). A thin veneer of Holocene alluvium overlies the late Pleistocene river terraces.

The past 10,000 years record floodplain and river terrace deposits in the Santa Cruz Valley, alluvial fan formation along the mountain front, and locally-derived colluvium on moderately steep hillslopes in the mountains. River terraces tend to be planar, although small channels are common. They are covered with sand and finer sediments.

Holocene channels on the piedmont that formed from 10,000 to 2,000 years ago (map units "Qy2" and "Qy1") are generally incised less than 1–to-2 m (3-to-6 ft) below the adjacent terrace or fan. They consist of a single, high-flow channel or multiple, low-flow channels with gravel bars (Youberg and Helmick 2001). Boulders, cobbles, sand, and silt have been deposited in the channels.

Modern channels less than 150 years old (map unit "Qycr") along the Santa Cruz River are typically entrenched several meters below adjacent terraces. The entrenched channel morphology began to evolve in the late 1800s (Betancourt 1990). Moderate to large flow events caused by flooding and debris flows continue to produce high channel velocities that may increase lateral bank erosion.

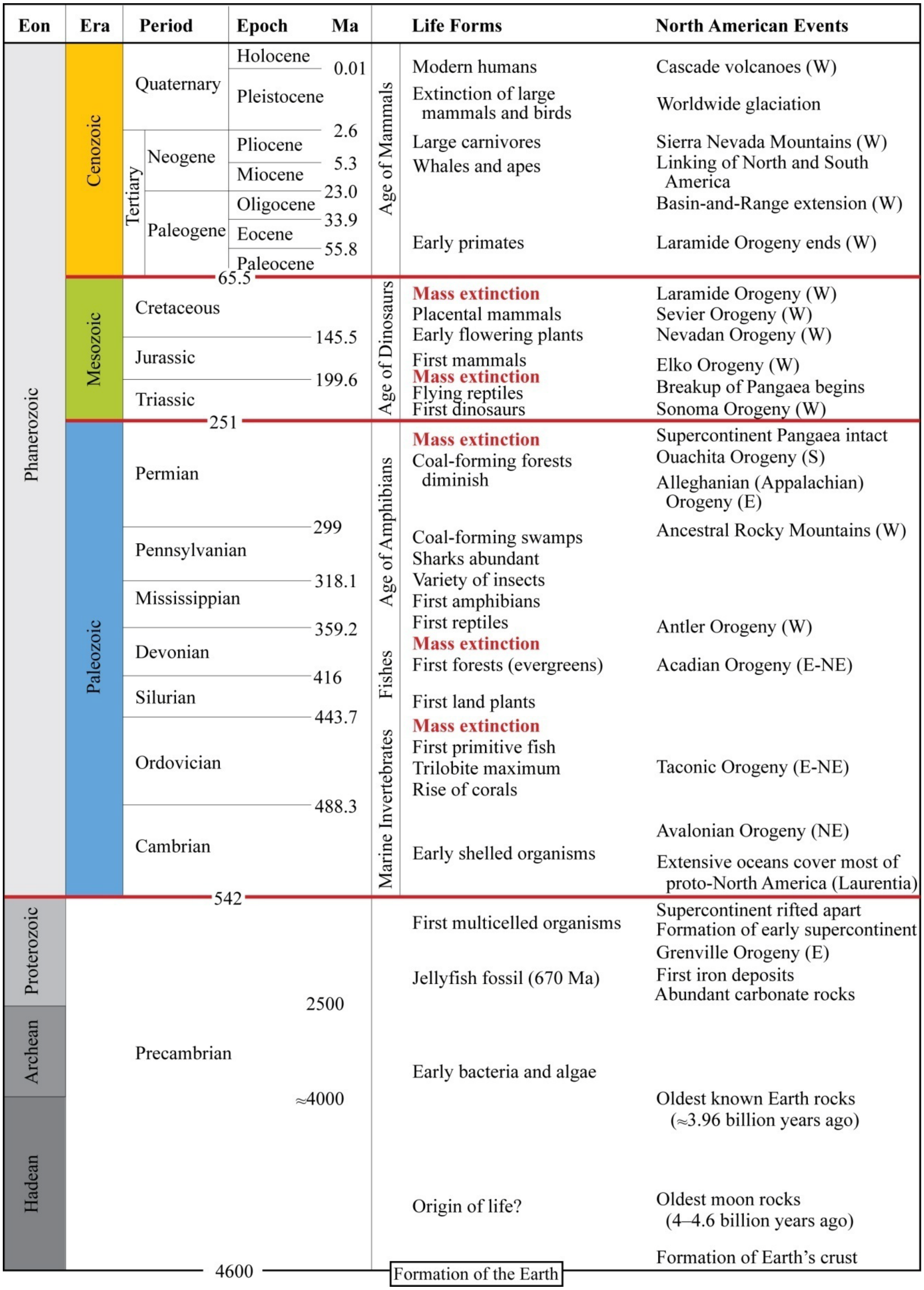


Figure 18. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015/ with additional information from the International Commission on Stratigraphy. http://www.stratigraphy.org/view.php?id=25.

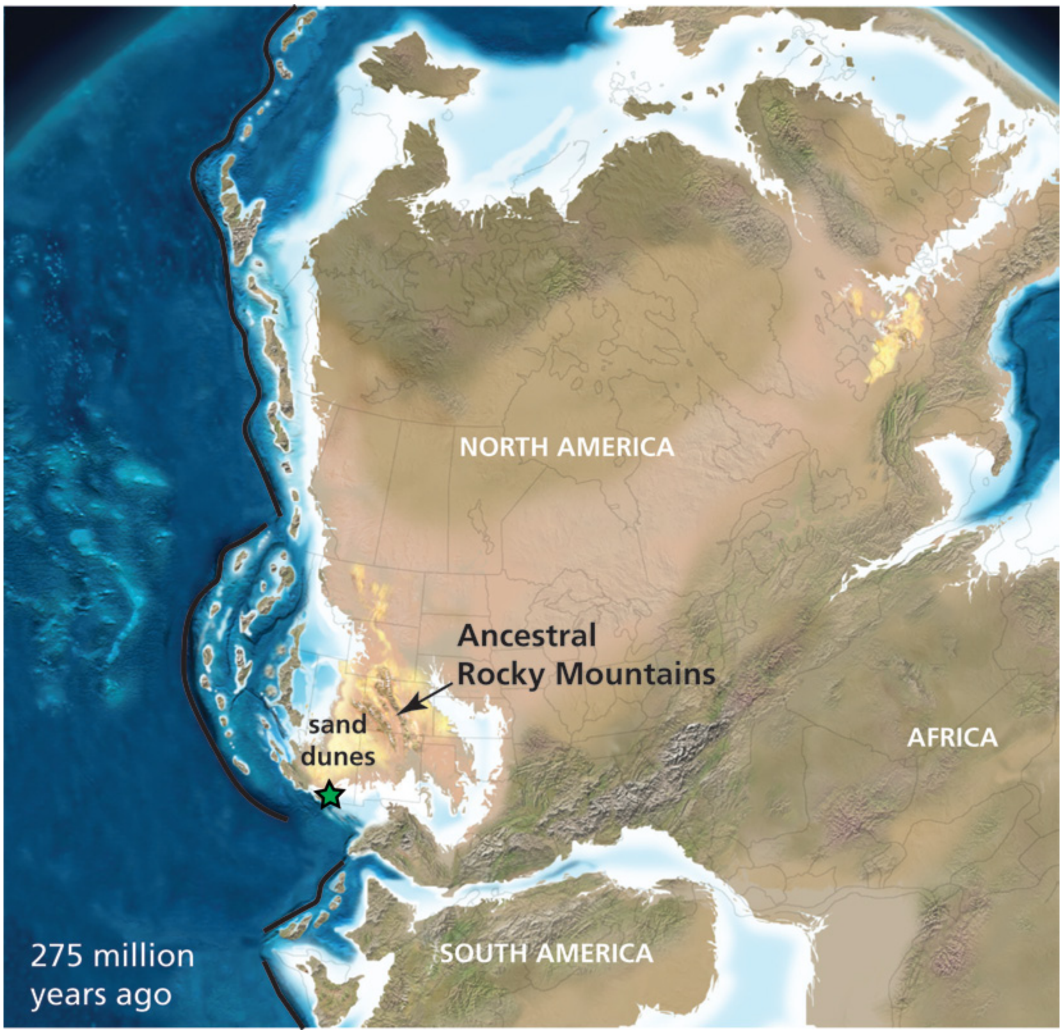


Figure 19. Middle Permian (275 million years ago) paleogeographic map of North America. Remnants of the northwest-southeast trending Ancestral Rocky Mountains (dark brown) can still be seen in Colorado. The light brown color in northeastern and central Arizona represents sand deposited in an arid dune environment. Basins in southeastern Arizona and southwestern New Mexico close as proto-South America collides with proto-North America. The dark line bordering the western shoreline marks the location of the subduction zone off the western margin of the land mass that will soon become the supercontinent, Pangaea. The green star represents the approximate location of today's Tumacácori National Historical Park. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base paleogeographic map by Ron Blakey, Colorado Plateau Geosystems, Inc., available online: http://cpgeosystems.com/namP275.jpg, accessed August 25, 2011. Annotation by the author.

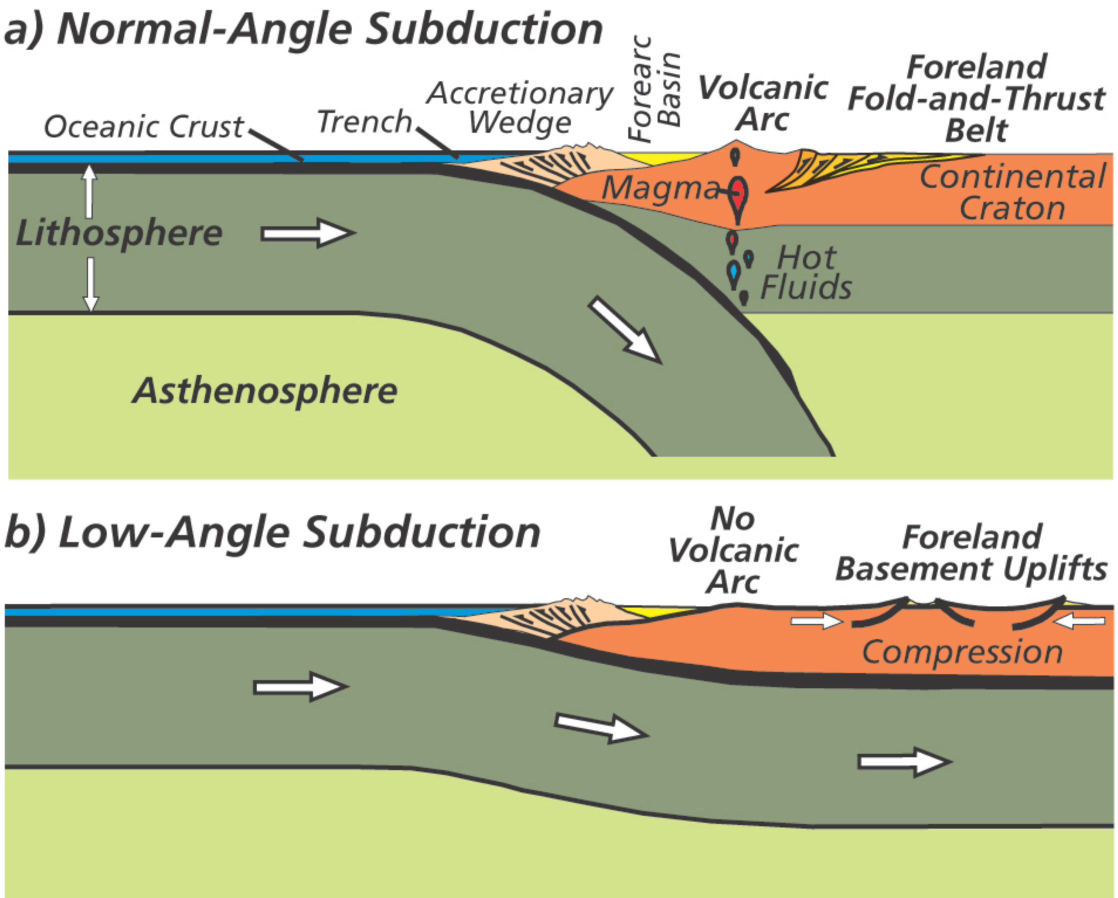


Figure 20. Normal-angle and low-angle subduction diagrams. A) In a normal plate-tectonic setting, a relatively steep angle of subduction causes melting above the downgoing slab. Magma rises to the surface and erupts, forming a chain of volcanoes (volcanic arc) along the continental margin, similar to the present Andes Mountains of South America. Sedimentary strata are folded and thrust toward the continental craton in a "foreland fold-and-thrust belt."In the Triassic, oceanic-oceanic plate convergence caused the volcanic arc to form offshore. During the Jurassic, the oceanic plate collided with the North American continent and the volcanic arc formed along the western margin of North America, as depicted in this diagram. B) During the Laramide Orogeny, the subducting slab flattened out, and deformation occurred farther inland. The downgoing slab in low-angle subduction does not extend deep enough to heat up and produce magma so volcanism ceases or migrates toward the craton. The subducting slab transmits stress farther inland, causing hard rock in the crust to compress and break along reverse faults, forming basement uplifts such as those in today's Rocky Mountains. Diagram by Robert J. Lillie (Oregon State University), modified from Lillie (2005).

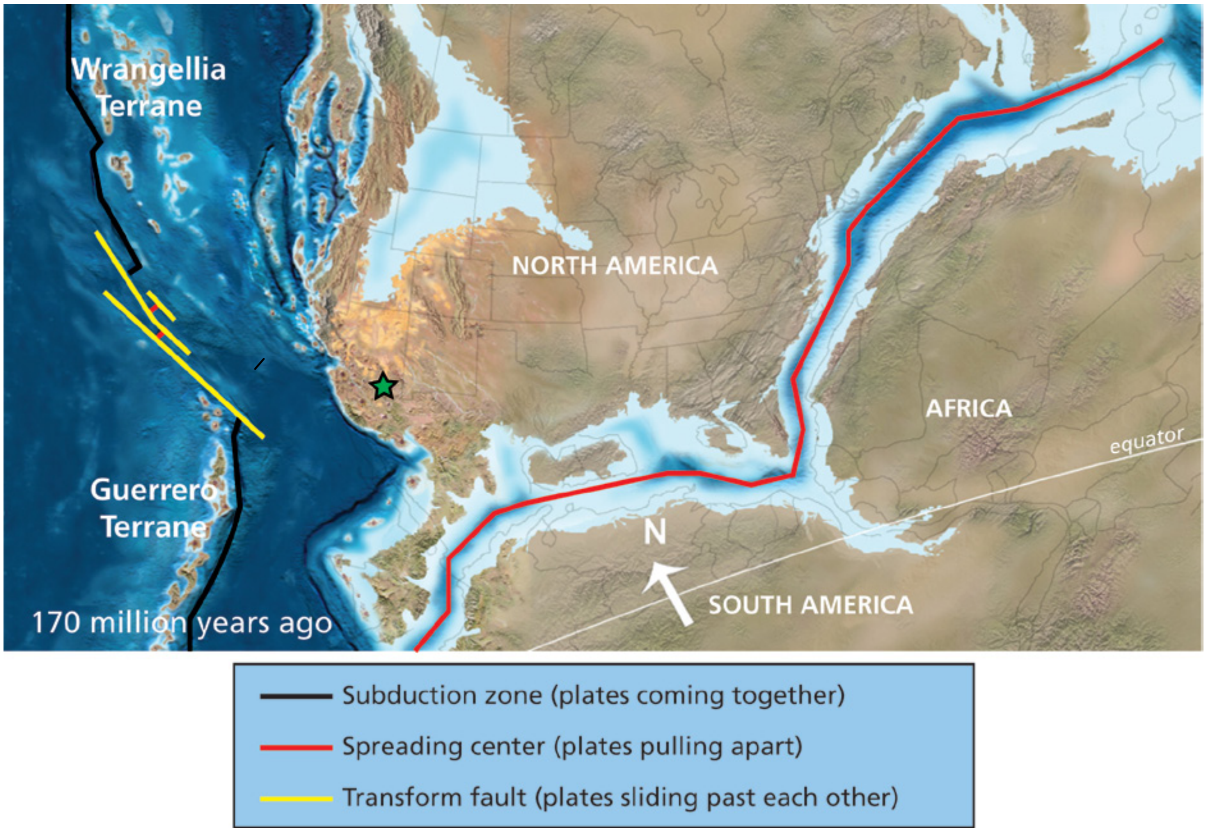


Figure 21. Middle Jurassic paleogeographic map of the southern half of the North American continent. Approximately 170 million years ago, the Greater Wrangellia Terrane collided with North America, forming a string of active volcanoes along the western margin from Mexico to Canada and causing thrust faulting in Nevada. The volcanic arc in the Wrangellia Terrane included today's Wrangell Mountains, the Queen Charlotte Islands, and Vancouver Island. The Guerrero Terrane closed to the south. The green star approximates the location of today's Tumacácori National Historical Park. A basin (foreland basin) formed landward of the thrusting in Nevada and allowed an epicontinental sea to encroach from the north. South America and Africa are rifting away from North America. The white line indicates the Middle Jurassic equator. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base paleogeographic map by Ron Blakey, Colorado Plateau Geosystems, Inc., available online: http://cpgeosystems.com/namJ170.jpg, accessed August 25, 2011. Annotation by the author.

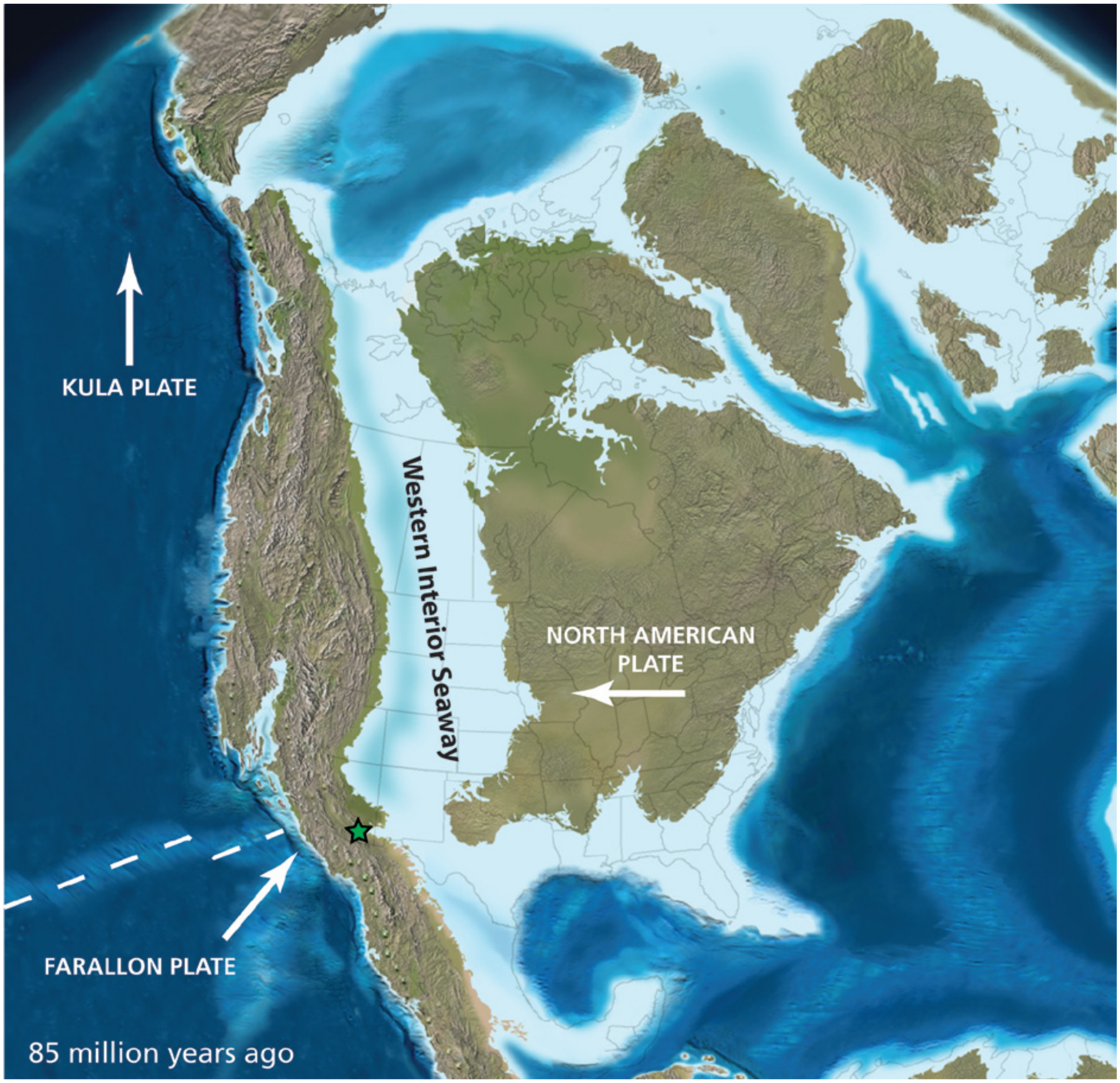


Figure 22. Late Cretaceous paleogeographic map of North America. Approximately 85 million years ago, the Western Interior Seaway reached its maximum extent. The Sevier Orogeny produced fold-and-thrust belt mountains along the western continental margin. Regional metamorphism affected western Arizona and eastern California. Paleozoic and Mesozoic sandstone, mudstone, and limestone were metamorphosed to quartzite, schist, and marble. The green star marks the approximate location of today's Tumacácori National Historical Park. Arrows indicate the general direction of plate movement. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Base paleogeographic map by Ron Blakey, Colorado Plateau Geosystems, Inc., available online: http://cpgeosystems.com/namK85.jpg, accessed August 25, 2011. Annotation by the author.

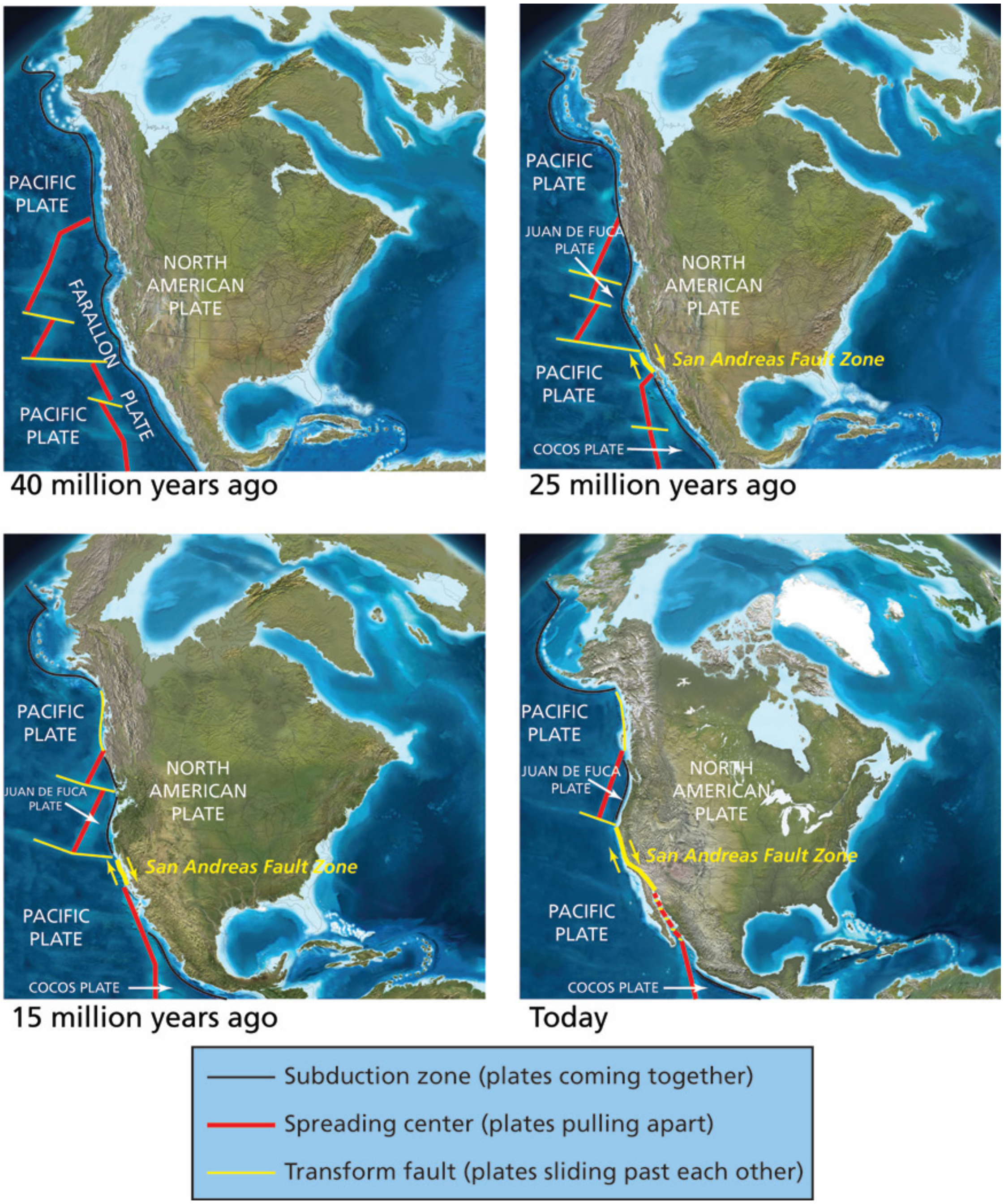


Figure 23. Growth of the San Andreas Fault System. When the spreading center between the Pacific plate and Farallon plate intersected the North American plate, a transform fault formed (San Andreas Fault zone), causing strike-slip (transpressional) movement. The Farallon plate has been subdivided into the Juan de Fuca plate, to the north, and the Cocos plate, to the south. Base paleogeographic maps by Ron Blakey, Colorado Plateau Geosystems, Inc., available online: http://cpgeosystems.com/nam.html, accessed August 25, 2011. Annotation and compilation by Jason Kenworthy (NPS Geologic Resources Division).

Geologic Map Data

This section summarizes the geologic map data available for Tumacácori National Historical Park. It includes a fold-out geologic map overview and a summary table that lists each map unit displayed on the digital geologic map for the park. Complete GIS data are included on the accompanying CD and are also available at the Geologic Resources Inventory (GRI) publications website: (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into the GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to create the digital geologic data for Tumacácori National Historical Park:

Simons. F. S. 1974. Geologic map and sections of the Nogales and Lochiel quadrangles, Santa Cruz County, Arizona. Miscellaneous Investigations Map I-762 (scale 1:48,000). U. S. Geological Survey, Reston, VA, USA.

Youberg, A. and W. R. Helmick. 2001. Surficial geology and geologic hazards of the Amado-Tubac area, Santa Cruz and Pima Counties, Arizona. Digital Geologic Map 13 (DGM-13) (scale 1:24,000). Arizona Geological Survey , Tucson, AZ, USA.

These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Tumacácori National Historical Park using data model version 2.1.

GRI digital geologic data for Tumacácori National Historical Park are included on the attached CD and are available through the NPS Natural Resource Information Portal (https://nrinfo.nps.gov/Reference.mvc/Search). Enter "GRI" as the search text and select Tumacácori National Historical Park from the unit list. The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A PDF document (tuma_geology.pdf) that contains all of the ancillary map information and graphics, including geologic unit correlation tables and map unit descriptions, legends, and other information captured from source maps.
- An ESRI map document file (tuma_geology.mxd) that displays the digital geologic data

Geology data layers in the Tumacácori National Historical Park GIS data.

Data Layer	Code	On Geologic Map Overview?
Geologic Cross Section Lines	SEC	No
Geologic Attitude Observation Points	ATD	No
Mine Point Features	MIN	No
Map Symbology	SYM	Yes
Linear Dikes	DKE	Yes
Folds	FLD	Yes
Faults	FLT	Yes
Geologic Contacts	GLGA	Yes
Geologic Units	GLG	Yes

Note: All data layers may not be visible on the geologic map overview graphic.

Geologic Map Overview Graphic

The fold-out geologic map overview displays the GRI digital geologic data draped over a shaded relief image of Tumacácori National Historical Park and includes basic geographic information. For graphic clarity and legibility, not all GIS feature classes are visible on the overview. The digital elevation data and geographic information are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the fold-out map unit properties table correspond to the accompanying digital geologic data. Following overall structure of the report, the table highlights the geologic issues, features, and processes associated with each map unit. The units, their relationships, and the series of events the created them are highlighted in the "Geologic History" section. Please refer to the geologic timescale (fig. 18) for the geologic period and age associated with each unit.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scales (1:48,000 and 1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 24 meters/80 feet (horizontally) for the 1:48,000 map, and within 12 meters/40 feet (horizontally) for the 1:24,000 map, of their true location.

Please contact GRI with any questions.

Overview of Digital Geologic Data for Tumacácori National Historical Park

NPS Boundary

Geologic Contacts

- known or certain
- approximate
- water or shoreline
- subaqueous (inferred)

Faults

- normal fault, known or certain
- normal fault, concealed
- normal fault, queried
- normal fault, inferred
- reverse left-lateral strike-slip fault, inferred

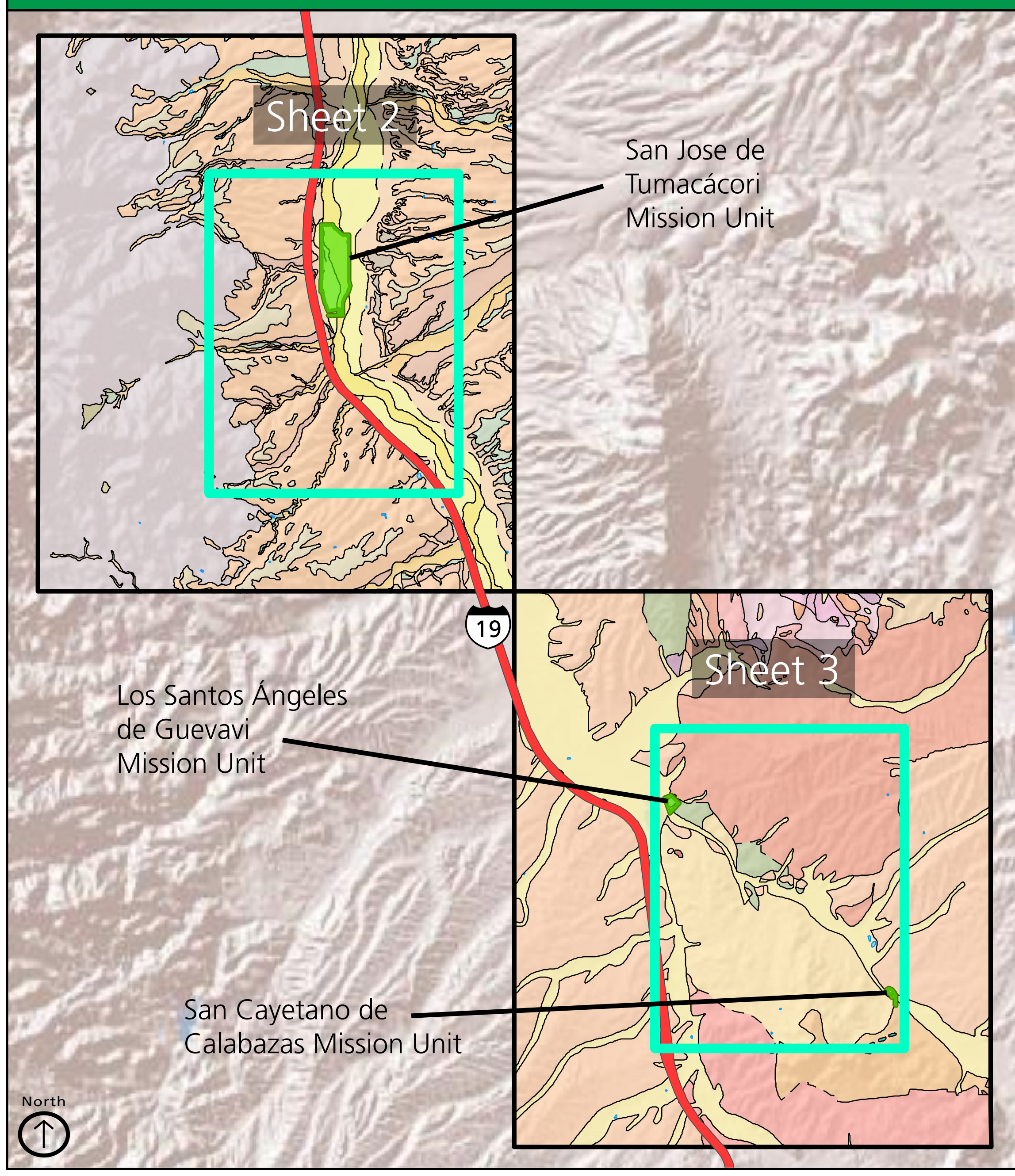
Folds

- syncline, concealed
- syncline, inferred

Linear Dikes

- r - Rhyolite or quartz dike, known or certain
- vein - Vein, known or certain
- dike - Lamprophyre dike, known or certain
- a - Aplite dike, known or certain

Full Extent of Digital Data, Areas of Detail in Blue



Geologic Units

- Water
- Qycr - Modern river channel deposits
- Qal - Younger alluvium and talus
- Qy2 - Late Holocene alluvium
- Qy1 - Holocene alluvium
- Qy - Undifferentiated Holocene alluvium
- Qyr - Holocene floodplain and terrace deposits
- Qlyr - Holocene to Late Pleistocene river terraces
- Ql - Late Pleistocene alluvium
- Qlr - Late Pleistocene river terraces
- Qm - Middle Pleistocene alluvium
- Qmr - Middle Pleistocene river terrace deposits
- Qo - Early Pleistocene alluvium
- QTs - Early Pleistocene to Pliocene alluvium
- QTal - Older alluvium
- Tn - Nogales Formation, undivided
- Tnl - Nogales Formation, lower Member
- R - Bedrock, undifferentiated
- Ks - Salero Formation
- p - Microdiorite plug
- Jb - Quartz Monzonite of Mount Benedict, biotite-hornblende quartz monzonite
- Jbm - Quartz Monzonite of Mount Benedict, quartz monzonite
- s - Metasedimentary rocks

This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters /40 feet (horizontally) of their true location.

This figure was prepared as part ofthe NPS Geologic Resources Division's Geologic Resources Inventory. The source maps used in creation of the digital geologic data product were:

Simons, F.S. 1974. Geologic Map of Sections of the Nogales and Lochiel Quadrangles, Santa Cruz County, Arizona (scale 1:48,000). Map I-762. U.S. Geological Survey.

Youberg, A., and Helmick, W.R. 2001. Surficial Geology and Geologic Hazards of the Amado-Tubac Area, Santa Cruz and Pima Counties, Arizona (scale 1:24,000) Digital Geologic Map 13 (DGM-13, Plate2). Arizona Geological Survey.

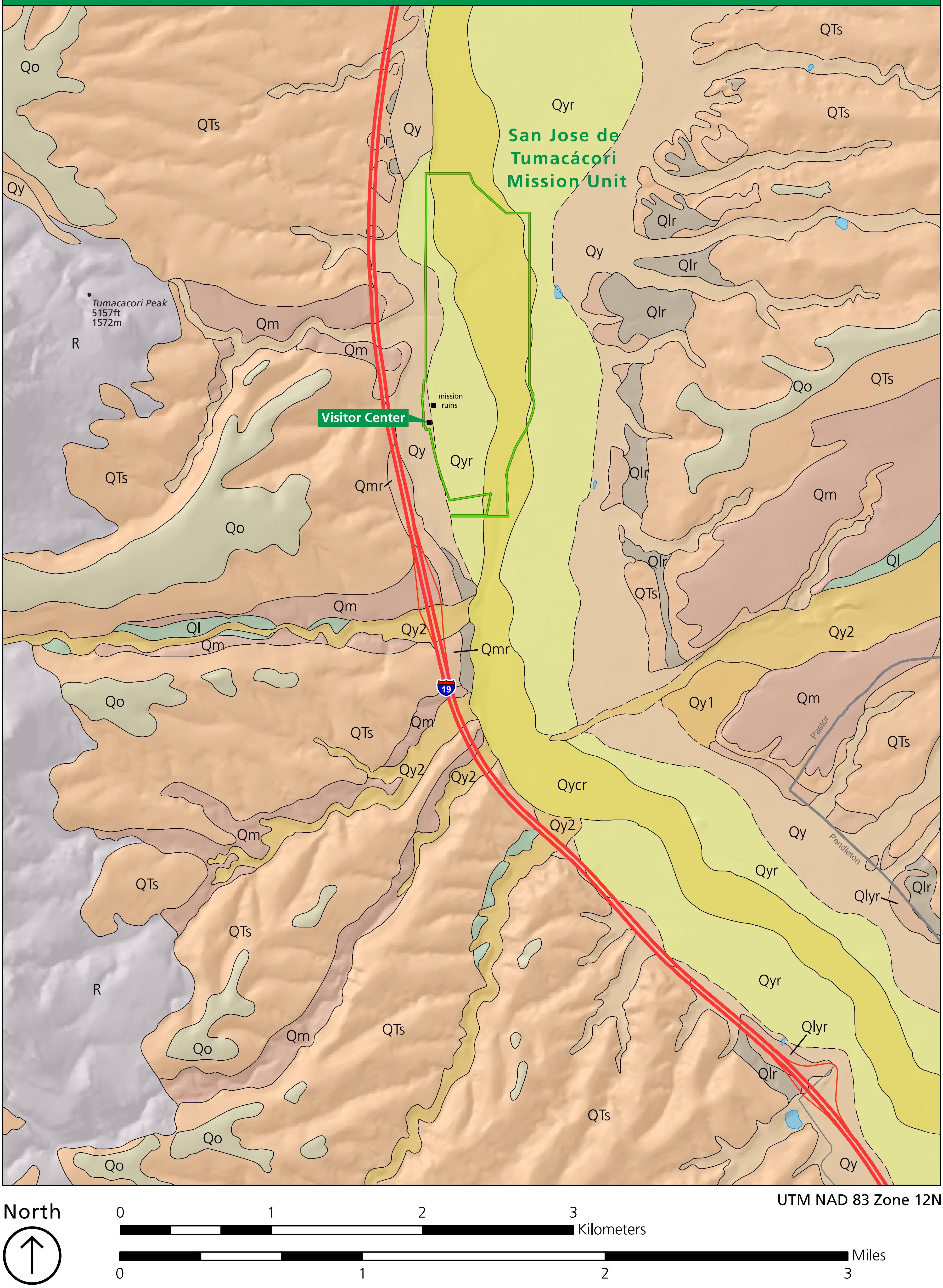
Digital geologic data and cross sections for Tumacácori National Historical Park, and all other digital geologic data prepared as part of the Geologic Resources Inventory, area available online at the NPS Natural Resource Information Portal: https://nrinfo.nps.gov/Reference.mvc/Search. (Enter "GRI" as the search text and select Tumacácori National Historical Park from the unit list.)

Produced by the Geologic Resources Inventory

September 2011

Overview of Digital Geologic Data for Tumacácori National Historical Park

Sheet 2: San Jose de Tumacácori Mission Unit



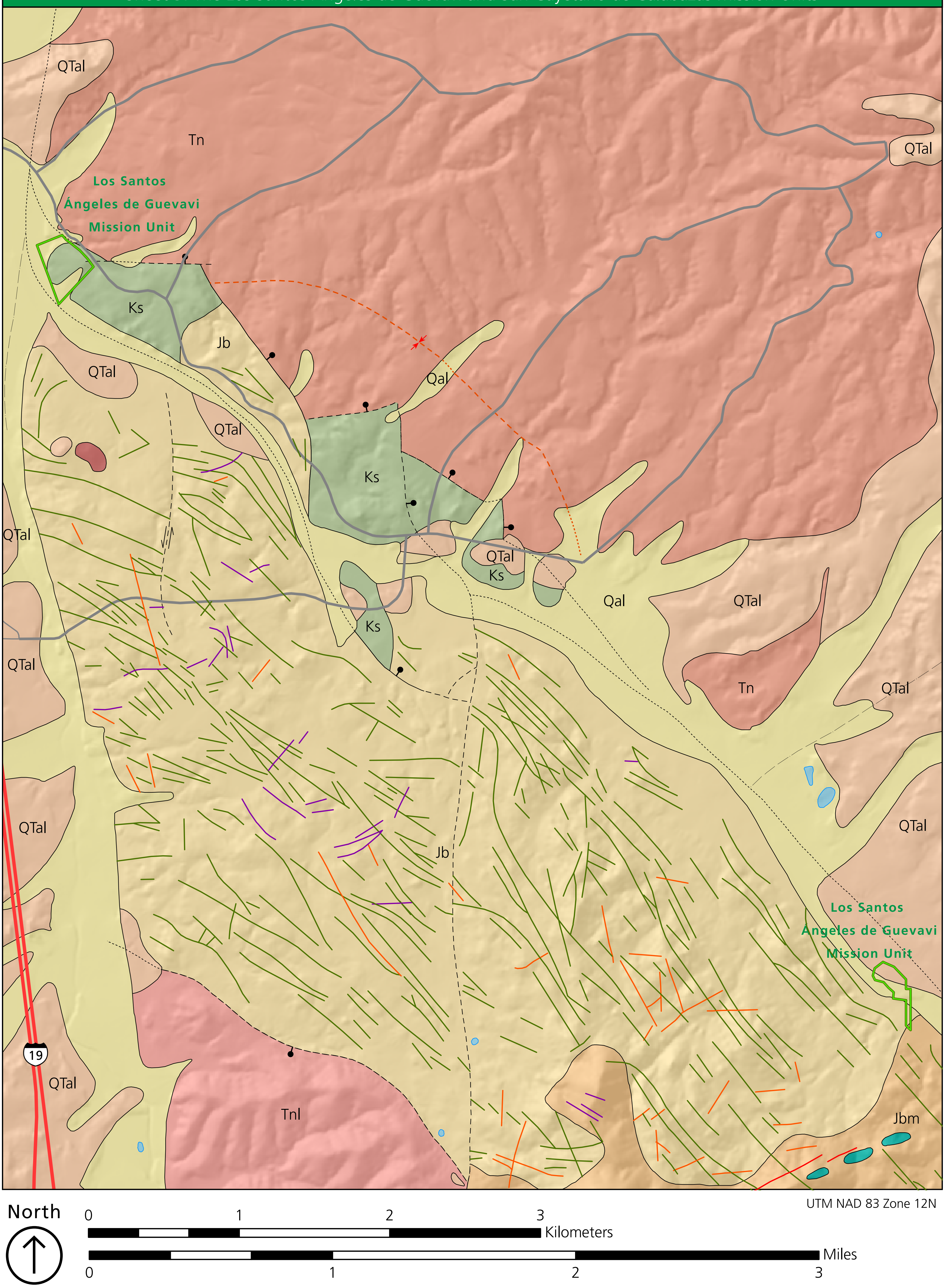
UTM NAD 83 Zone 12N

Produced by the Geologic Resources Inventory

September 2011

Overview of Digital Geologic Data for Tumacácori National Historical Park

Sheet 3: The Los Santos Ángeles de Guevavi and San Cayetano de Calabazas Mission Units



Produced by the Geologic Resources Inventory

September 2011

Map Unit Properties Table: Tumacácori National Historical Park

Colored rows indicate units mapped within Tumacácori National Historical Park. Colors are based on U.S. Geological Survey standard timescale colors.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY (Holocene)	Modern river channel deposits (Qycr)	Less than 150 years old. Primarily sand and gravel, river channel deposits of the Santa Cruz River and Sopori Wash, about 18 km (11 mi) north of the Tumacácori Mission Unit. Channels are entrenched several meters below adjacent young terraces along the Santa Cruz River and are extremely flood prone. Moderate to large flow events produce deep, high velocity channels. In the map area, generally unprotected channels are subject to severe lateral erosion during floods.	Low. Susceptible to lateral erosion	River channel. Potential damage to bridges and trails during floods.	Flooding and debris flows. Bank collapse.	Subject to washing away during flooding.	Sand and gravel.	Cottonwood – willow riparian environment.	Hiking trail. Water unsafe to touch.	History of channel incision; current erosional processes.
	Alluvium and Talus (Qal)	Younger alluvium and talus. No further description given by Simons (1974).	Low.	Roads, buildings, infrastructure.	Flash flooding.	Potential cultural sites.	Sand and gravel.	Ephemeral stream vegetation.	Roads near units.	Current erosional processes.
	Alluvium (Qy2, Qy1)	Qy2: Late Holocene (less than 2,000 years old). Channels, low terraces, and small alluvial fans of cobbles, sand, silt and boulders. Deposited by modern drainages. Sand and finer sediment typically mantle terraces. Generally, channels are incised less than 1 m (3 ft) below adjacent terraces and fans. Locally, incision may be as much as 2 m (7 ft). Terrace and fan surfaces are brown, and generally appear darker than surrounding areas on aerial photos; sandy to gravelly channels appear light-colored on aerial photos (fig. 15). Qy1: Approximately 2,000 to 10,000 years old. Scattered, low terraces along incised drainages on the piedmonts. Inundation of the slightly higher Qy1 surfaces is less than adjacent Qy2. Generally, planar surfaces with local relief as much as 1 m (3 ft) where gravel bars are present. Surfaces are: 1) less than 2 m (7 ft) above adjacent active channels, 2) typically sandy but may have gravel lags, 3) fairly dark on aerial photos, but light-colored where a gravel lag is present. Alluvial fan channels form weakly integrated distributary (branching downstream) systems. Units are mapped east of the Santa Cruz River; south of the Tumacácori Unit.	Low. Unconsolidated fine sediment is less resistant to erosion than cobbles and boulders.	Roads and borrow pits.	Unknown.	American Indian and early settler sites are possible.	Sand and gravel.	Dense mesquite, acacia, ash and willow; dense shrubs and grass. Smaller washes contain mesquite, acacia and shrubs.	Hiking and potential off-road use.	Provides data for channel incision history.
	Undifferentiated alluvium (Qy)	Less than 10,000 years old. Smaller incised drainages on the piedmonts and more extensive young alluvial fans at the base of the piedmonts, adjacent to the Santa Cruz floodplain. Includes both Qy2 and Qy1 deposits. Used where exposures did not allow differentiation between Qy1 and Qy2 surfaces at a 1:24,000 scale. Mapped on the western edge of the Tumacácori Unit.	Low, especially finer-grained sediment.	Limited areal extent in the park.	Incised drainages. Erosion potential.	American Indian and early settler sites are possible.	Material for adobe bricks (?)	Qy1 and Qy2 vegetation types.	Limited exposure.	History of Quaternary channel incision.
	Floodplain and terrace deposits (Qyr)	Less than 10,000 years old. Weakly to unconsolidated sand, silt, and clay on floodplains and terraces flanking the main channel system along the Santa Cruz River and Sopori Wash. Terrace surfaces are flat and uneroded, except immediately adjacent to channels. Typically altered to agricultural fields or urban development. Some surfaces are part of the active floodplain and may be inundated in large floods. However, most terraces were abandoned during the arroyo cutting of the late 1800s and are no longer part of the active floodplain. Local surfaces may experience sheetflooding during large floods in areas where the main channel is not deeply entrenched, and because of flooding on local tributaries that discharge onto Qyr surfaces.	Unprotected channel banks formed in Qyr deposits are very susceptible to lateral erosion.	Primary surface of Tumacácori Unit. Underlies buildings, roads, paths.	Sheet flooding during large flood events.	Agricultural, early settler, or American Indian sites.	Sand and clay for adobe bricks (?)	Ash, Hackberry, and Mexican elderberry mix with mesquite, acacia and palo verde trees near riparian corridor.	Forms the surface at Tumacácori Mission Unit.	History of channel incision over the last 10,000 years.
	Hillslope colluvium (Qc)	Locally-derived deposits on moderately steep hill slopes in the mountains. Clay to cobbles and boulders; very poorly sorted. Subangular to angular clasts deposited close to the point of origin. Mapped only where the unit can be identified in aerial photographs; not mapped in the park.	Variable.	Unstable slopes.	Potential landsliding.	Hillslopes may be adjacent to cultural sites.	Unknown.	Vegetation limited by slope and aspect.	Limited potential.	None.
QUATERNARY Pleistocene Upper	River terrace deposits and alluvium (Ql, Qlr, Qlyr)	Approximately 130,000 to 10,000 years old. Surfaces commonly have loose lags of pebbles and cobbles. Ql and Qlr clasts have weak to moderate rock varnish. Light orange to dark orange on color aerial photos (fig. 15). Ql: Pebbles, cobbles, and finer-grained sediment on slightly to moderately dissected relict alluvial fans and terraces. Found on the upper, middle and lower piedmont. Moderately to well developed, slightly to moderately incised tributary drainage networks. Active channels incised up to about 2 m (7 ft) below Ql surfaces. Incision typically increases toward the mountain front, and toward the southern end of the Santa Cruz Valley. Fans and terraces are commonly lower in elevation than adjacent Qm and older surfaces, but the lower margins of Ql deposits lap out onto more dissected Qm surfaces in some places. Qlr: Gravels, cobbles, and finer-grained sediment form river terraces typically 3 to 5 m (10 to 16 ft) above Qlyr terraces. Often intermixed with late Pleistocene distal piedmont Ql deposits along drainages. Qlyr: Unit Qlr overlain by thin veneers of units Qy, Qy2 and Qy1. Terrace deposits 2 to 3 m (7 to 10 ft) above Qyr floodplains. Reddened Pleistocene alluvium exposed in patches on low ridges, in roads, and cut banks of washes. Holocene surfaces usually are light brown. The units are not mapped in the park.	Low to variable. Coarse-grained material is more resistant to erosion than finer-grained sediment.	Gradual slopes would make this unit attractive to residential and commercial development.	Unknown.	Potential for American Indian and early settler sites.	Sand and gravel. Sand and clay for adobe bricks (?)	Ql: Grasses, small shrubs, cholla, prickly pear, barrel cacti, and mesquite. Ocotillo where carbonate parent material exists. Qlr: Vegetation is sparse; mesquite, grasses.	Limited surface exposures.	History of channel incision.

Age			Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY	Pleistocene	Middle	Alluvium (Qm) River terrace deposits (Qmr)	Approximately 750,000 to 130,000 years old. Neither unit is mapped in the park. Qm: Well-preserved, planar, reddish-brown surfaces. Scattered pebble and cobble lags form moderately to highly dissected alluvial fans and terraces. Drained by well developed, moderately to deeply incised tributary channel networks. Dissection increases towards the mountains and the southern end of the map area. More eroded, rounded surfaces have scattered cobble lags with moderate to strong orange or dark brown rock varnish and broad, ridge-like topography. Well-preserved surfaces have a distinctive dark red color on color aerial photos (fig. 15). Qmr: Boulders, cobbles, gravels and finer-grained sediment. High, scattered river terrace remnants on unit QTs. Typically 45 to 50 m (150 to 160 ft) above the modern Santa Cruz River. Less than 2 m (7 ft) thick. Reddish-orange in color aerial photos, reflecting reddening of surface clasts and soil (fig. 15).	Low to variable. Coarse-grained material is more resistant to erosion than finer-grained sediment.	Unstable surface exposures, shrink/swell clay, and incised tributary channels may pose a challenge for development.	Erosion potential. Some clays in Qm will swell when wet and shrink upon drying (shrink/swell potential).	Potential for American Indian and early settler sites.	Sand and gravel.	Grasses, cholla, prickly pear, barrel cacti, mesquite, and ocotillo.	The unit may be transected by roads and trails.	History of channel incision.
QUATERNARY	Pleistocene	Lower	Alluvium (Qo)	Approximately 750,000 to 2 million years old. Cobbles, boulders, sand and finer clasts form very old alluvial fan remnants on top of highly dissected basin fill deposits (unit QTs). Surfaces are moderately to well-preserved with strong soil development. The unit is best preserved on the upper piedmonts near the mountain fronts. Unit is not mapped within the park.	Moderate. Stabilized by soil development.	Any infrastructure may be impacted by flash flooding or sheetflow on upper piedmont surfaces.	Some potential for swelling clays. Underlies ephemeral streams with flash flood potential.	Potential early settler, ranching, and American Indian sites.	Potential boulders for landscaping designs.	Mesquite, ocotillo, scattered cacti, and grasses dominate.	Possible hiking and horse trails along mountain front and upper piedmonts.	Surfaces record highest levels of aggradation in the Santa Cruz Valley.
QUATERNARY / NEOGENE	Pleistocene / Pliocene		Alluvium (QTs)	Approximately 1 million to 5 million years old. Subangular to subrounded boulders, cobbles, and gravels with layers and lenses of sand, silt and clay. Basin fill consisting of very old, deeply dissected and highly eroded alluvial fan deposits derived from nearby mountains. Moderately indurated. Eroded ridges alternate with deep valleys. Drained by deeply incised tributary channel networks. Most predominant valley unit outside the park boundaries. Thickness varies from a few meters near the mountains to 260 m (850 ft) near Amado, about 16 km (10 mi) north of the Tumacácori Mission Unit.	High. Resistant due to large clasts size and carbonate accumulation.	Deep, incised channel networks should discourage development.	Potential flash flooding in incised drainages.	Potential early settler and American Indian sites.	Sand and gravel. Potential boulders for landscaping designs.	Grasses with scattered cacti, mesquite, acacia, and ocotillo.	Informal trails and potential for off-road vehicle use.	History of channel incision.
NEOGENE	Pliocene		Quaternary and Tertiary Older alluvium (QTal)	Slightly-to-moderately consolidated alluvium. Indurated. Forms cliffs in canyons northeast of the Guevavi Mission Unit.	Moderate. Partly consolidated.	Underlies roads, Guevavi Mission ruins, Nogales International Airport and other buildings.	Potential rockfall from cliffs northeast of the park.	Mission ruins. Potential sites of American Indians.	Sand and gravel.	Mesquite and acacia trees; cholla and barrel cacti.	Mission closed to the public.	History of basin filling.
NEOGENE	Miocene		Nogales Formation, undivided (Tn)	Epiclastic volcanic conglomerate containing abundant beds of sandstone and grit. Clasts are from the Grosvenor Hills Volcanics, north of the Calabazas Mission Unit. Forms Cuates Buttes, immediately north of the Calabazas Unit.	High.	Should provide a relatively stable foundation.	Unknown.	Potential American Indian sites outside park.	None.	Mesquite scrub environment.	Mission closed to the public.	Type locality is Nogales, AZ.
NEOGENE	Miocene		Nogales Formation Lower Member (Tnl)	Light-gray to light-brown (rarely pale-red) conglomerate, fanglomerate, tuffaceous conglomerate and sandstone, and tuff; contains beds of water laid silicic tuff and tuffaceous sandstone. Coarse fanglomerate composed of granitic detritus along the upper Santa Cruz River grades westward toward Nogales into epiclastic volcanic conglomerate containing minor granitic components. Thickness may be as much as 1,500 m (5,000 ft). Mapped south of the Guevavi Unit.	Erosion resistance will depend on matrix cement.	High. Underlies buildings, roads, and most of Nogales, AZ.	Unknown.	Potential sites of early settlers and American Indians. Modern culture.	No significant minerals in the unit.	Mesquite scrub environment.	Not applicable with regard to activities within park boundaries.	Named for exposures east, in, and north of Nogales, AZ.
PALEOGENE	Oligocene		Bedrock, undifferentiated (R)	Extrusive rhyolite and rhyodacite of the Tumacácori Mountains, west of the Tumacácori Mission Unit. Light-gray to grayish-pink, vitric to fine-grained, porphyritic lava flows, welded tuff, pyroclastic rocks, and some epiclastic rocks. Commonly a few tens to a few thousands of meters thick. Dated at 23, 24, 25, 26, and 27 million years old (Drewes 1980). Drewes (1980) labeled the unit "Tv." The unit is not mapped in the park.	High.	Steep slopes and canyons present challenges for construction.	Rockfall.	Potential sites of American Indians, early settlers, miners.	Unknown. Some prospect pits.	Mountain vegetation.	Backcountry activities in Tumacácori Mountains.	Record extensive upper Oligocene to lower Miocene volcanic activity.

Age		Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
PALEOGENE	Oligocene	Latite (?) dike (Tla)	Light-brownish-gray, 4.6 to 7.6 m (15 to 25 ft) thick; contains a few small phenocrysts of plagioclase, augite, and altered hornblende(?). Linear features in the Grosvenor Hills. Mapped in the San Cayetano Mountains.	High.	Low (linear features).	None. Linear exposures.	Linear feature.	Plagioclase, augite.	Mesquite scrub environment.	Not applicable.	Crosscutting relationships help age-date the igneous rocks.
PALEOGENE	Oligocene	Biotite-hornblende rhyodacite (Tr)	Brownish- to pinkish-gray, porphyritic; plugs and dikes. Mapped in the Grosvenor Hills. Mapped north of Cuates Buttes (north of the Calabazas Unit).	High.	Limited areal extent.	Minor rockfall.	Limited areal extent.	Biotite, hornblende .	Mesquite scrub environment.	Not applicable.	
PALEOGENE	Oligocene	Grosvenor Hills Volcanics (Thr, Thb, Thl, Tht)	Mapped in Grosvenor Hills, which includes Fresno Canyon, approximately 5.5 km (3.4 mi) north of the Calabazas Mission Unit, and Ash Canyon, about 10 km (6 mi) northeast of the Calabazas Unit. Thr: Light-brownish-gray to pale-red, coarse-grained, hornblende-biotite rhyodacitic or dacitic tuff. Thb: Grayish-red, brownish-gray, or light-gray, coarse-grained porphyritic biotite-hornblende rhyodacitic tuff, agglomerate, and flow breccia. Rhyodacitic agglomerate in upper part has blocks up to 1 m (3 ft) across. West of Fresno Canyon, flow breccia is overlain by a 1.2-m (4-ft) layer of chalcedony, and tuff breccia. East of Fresno Canyon, the unit contains some gray to grayish-red hornblende-hypersthene-biotite vitrophyre. Thl: Biotite latite. Gray, porphyritic, with conspicuous flow layering. West of Ash Canyon, base of Thl has massive flow breccia as thick as 30 m (100 ft). Some light-colored biotite rhyolite welded tuff in Ash Canyon. Tht: Orange-pink to pink or light-gray biotite rhyolitic vitric-lithic tuff. Thick-bedded, moderately consolidated, and pebbly. Many 0.3-m (1-ft) layers of pebble conglomerate and a few beds of boulder conglomerate as much as 3 m (10 ft) thick; silicic volcanic lithic clasts. In upper Fresno Canyon, lower part includes beds of rhyolite (“r”), well-bedded tuffaceous sandstone and tuff (“s”), and porphyritic biotite(?) andesite and andesitic agglomerate (“a”).	High.	Volcanic rock would provide firm foundation, but building on faults should be avoided.	Potential rockfall on steep slopes and cliffs.	Potential sites of American Indians, early settlers, and miners.	Hornblende, biotite, augite, hypersthene, and chalcedony.	Mesquite scrub environment. Mesquite and acacia trees; cholla and barrel cacti.	Limited areal extent.	Equivalent to Tv mapped by Drewes (1980). Radiometric age dates of 27 and 28 million years old (Oligocene).
PALEOGENE	Eocene	No deposits of this age in the map area									
PALEOGENE	Paleocene	Heterogeneous volcanic and volcaniclastic rocks (Tgga)	Mostly gray, greenish-gray, or reddish-purple pyroxene andesite lava and flow breccia. Contains some andesitic tuff and breccia, light-gray to pink latitic to rhyolitic tuff and lava, and coarse volcanic conglomerate. Mapped north of the Calabazas and Guevavi Units in Ash Canyon, Mary Kane Canyon, and at the head of Guebabi Canyon, which is located between the Calabazas and Guevavi Units.	High.	Not applicable. Limited exposures.	Unit is mapped on gradual slopes with limited rockfall or other hazard potential.	Limited areal extent.	Pyroxene.	Mesquite scrub environment.	Not applicable; limited areal extent.	Equivalent to Tv of Drewes (1980). Oligocene?
CRETACEOUS	Upper	Salero Formation (Ks)	Gray, grayish-red, greenish-gray, or olive-brown arkosic (feldspar-rich) sandstone and pebbly sandstone; includes minor conglomerate and silicic tuff and welded tuff. Principal detrital minerals are plagioclase and potassium feldspars; less abundant components are quartz, biotite, and volcanic rock fragments. In the lower Santa Cruz River and within the Calabazas Unit, Ks is a gray, locally pale-red, distinctly bedded epiclastic volcanic conglomerate that contains subangular clasts as large as 0.3 m (1 ft) in diameter, although most clasts are less than 2.54 cm (1 in) in diameter. Volcanic rocks dominate the unit, but granitic rocks, diabase, aplite, and quartzite are also present. Unconformable contact with Jb. Thickness probably 610 m (2,000 ft) or more.	Variable. Welded tuff more resistant than sandstone.	Probably would provide a firm foundation. Strata dip about 35° to 40° west, but topography is relatively flat.	No major hazards.	Mapped in fault blocks of limited areal extent. Potential sites of American Indian and early settlers.	Plagioclase and potassium feldspars.	Rocky ground. Mesquite and “Coyote gourds” (Calabazas means "squash" or "gourds" in Spanish).	Mission closed to the public.	Derived from Jurassic granitic rocks and Triassic-Jurassic volcanic rocks.
CRETACEOUS	Lower	No deposits of this age in the map area.									
JURASSIC	Upper										

Age		Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
JURASSIC	Middle	Quartz Monzonite of Mount Benedict (Jb, Jbm)	Minor exposures are mapped within the southern border of the Guevavi Mission Unit. Jb: Biotite-hornblende quartz monzonite. Light- to light-brownish-gray, coarse porphyritic; contains some granodiorite and quartz diorite. Mineral composition: 20% quartz, 36% plagioclase feldspar, 36% perthitic potassium feldspar, 4% biotite, 3% pale-green hornblende, and 1% accessories, mainly sphene. Radiometric ages range from approximately 164 to 160 million years old (K-Ar dates on biotite and hornblende). Jbm: Quartz monzonite. Light brown to light-gray, fine- to coarse-grained; contains abundant fine-grained or aplitic quartz monzonite on Mount Benedict, and much epidote-quartz-chlorite rock (epidosite) north and east of Mount Benedict. Probably is older than Jb. Numerous northwest-to-southeast trending, linear, lamprophyre dikes (see “dike” below) cut both units.	High.	Steep terrain. Jeep trails; roads; prospect pits and mines.	Potential rockfall in higher elevations. No major hazard in Guevavi Unit.	Remnants of past mining activities on Mount Benedict, but not within the park.	Plagioclase and potassium feldspar; biotite; epidote; hornblende ; quartz; sphene.	Mesquite scrub environment. Mesquite and acacia trees; cholla and barrel cacti.	Limited exposures in the park. Jeep trails, roads, and hiking available outside the park boundaries.	Jurassic igneous intrusions.
JURASSIC	Uncertain Age Assignment	Minor units within the Quartz Monzonite (Jb, Jbm) (r, s, p, a, dike, vein)	None of these units are mapped in the park. r: Rhyolite or quartz latite dike. May be Cretaceous or Tertiary in age. s: Metasedimentary rocks. Inclusions of gray to black vitreous quartzite and other metasedimentary (?) rocks. Three isolated outcrops of limited areal extent south of the Guevavi Mission Unit. p: Microdiorite plug. a: Aplite dike. Many unmapped. dike: Lamprophyre dike. Mainly greenish-gray hornblende-plagioclase lamprophyre (spessartite); some micro-diorite or diabase. Most dikes are 2 to 10 feet thick; maximum thickness is about 200 feet. Commonly somewhat altered to epidote, chlorite, and carbonate; some dikes completely reconstituted. Intrudes units Jb and Jbm. Age not indicated. vein: No description. Intrudes units Jb and Jbm. Age not indicated.	High.	Linear features with limited areal extent.	None.	Not applicable. Limited areal extent.	Unknown, but limited areal extent.	Mesquite scrub environment.	Not applicable. Limited areal extent.	Records igneous activity.

Reference maps:

1) Simons, F.S. 1974. Geologic map and sections of the Nogales and Lochiel quadrangles, Santa Cruz County, Arizona. U.S. Geological Survey Investigations Map I-762 (scale 1:48,000).

2) Youberg, A. and W. R. Helmick. 2001. Surficial Geology and Geologic Hazards of the Amado-Tubac Area, Santa Cruz and Pima Counties, Arizona. Arizona Geological Survey Digital Geologic Map 13 (DGM-13) (scale 1:24,000).

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

abyssal plain. A flat region of the deep ocean floor, usually at the base of the continental rise.

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

aggradation. The building-up of Earth's surface by depositional processes, specifically the upbuilding performed by a stream in order to establish or maintain uniformity of grade or slope.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

aplite. A light-colored intrusive igneous rock characterized by a fine-grained texture. Emplaced at a relatively shallow depth beneath Earth's surface.

arenite. A general term for sedimentary rocks composed of sand-sized fragments with a pure or nearly pure chemical cement and little or no matrix material between the fragments.

argillaceous. Describes a sedimentary rock composed of a substantial amount of clay.

arkose. A sandstone with abundant feldspar minerals, commonly coarse-grained and pink or reddish.

arroyo. A small, deep, flat-floored channel or gully of an ephemeral or intermittent stream in the arid and semiarid regions of the southwestern United States.

ash (volcanic). Fine material ejected from a volcano (also see "tuff").

asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.

augite. A dark-green to black pyroxene mineral that contains large amounts of aluminum, iron, and magnesium. Found in igneous and high-temperature metamorphic rocks.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

batholith. A massive, discordant pluton, larger than 100 km^2 (40 mi^2), and often formed from multiple intrusions of magma.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

block (fault). A crustal unit bounded by faults, either completely or in part.

braided stream. A sediment-clogged stream that forms multiple channels which divide and rejoin.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material such as tuff or ash.

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

claystone. Lithified clay having the texture and composition

colluvium. A general term for any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited through the action of surface runoff (rainwash, sheetwash) or slow continuous downslope creep.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental rise. Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; it generally has smooth topography but may have submarine canyons.

continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

continental shield. A continental block of Earth's crust that has remained relatively stable over a long period of time and has undergone minor warping compared to the intense deformation of bordering crust.

continental slope. The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.

convergent boundary. A plate boundary where two tectonic plates are colliding.

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

core. The central part of Earth, beginning at a depth of about 2,900 km (1,800 mi), probably consisting of iron-nickel alloy.

country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

dacite. A fine-grained extrusive igneous rock similar to andesite but with less calcium-plagioclase minerals and more quartz.

debris cone. A cone or mound of ice or snow on a glacier, covered with a veneer of debris thick enough to protect the underlying material from ablation.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

dip. The angle between a bed or other geologic surface and horizontal.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

downcutting. Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

epiclastic rock. A rock formed at Earth's surface by consolidation of fragments of pre-existing rocks.

epicontinental. Describes a geologic feature situated on the continental shelf or on the continental interior. An "epicontinental sea" is one example.

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

fanglomerate. A sedimentary rock of heterogeneous materials that were originally deposited in an alluvial fan and have since been cemented into solid rock.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

flat slab subduction. Refers to a tectonic plate being subducted beneath another tectonic plate at a relatively shallow angle.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

geology. The study of Earth including its origin, history, physical processes, components, and morphology.

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

groundmass. The material between the large crystals in a porphyritic igneous rock. Can also refer to the matrix of a sedimentary rock.

hanging wall. The mass of rock above a fault surface (also see “footwall”).

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

horn. A high pyramidal peak with steep sides formed by the intersection walls of three or more cirques.

horst. Areas of relative “up” between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see “graben”).

hypersthene. A greenish, black, or dark brown rock-forming mineral common in many igneous rocks.

hydrolysis. A decomposition reaction involving water, frequently involving silicate minerals.

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

latite. A porphyritic extrusive volcanic rock having large crystals of plagioclase and potassium feldspar minerals in nearly equal amounts, little or no quartz, and a finely crystalline to glassy groundmass.

lava. Still-molten or solidified magma that has been extruded onto Earth’s surface though a volcano or fissure.

left lateral fault. A strike slip fault on which the side opposite the observer has been displaced to the left Synonymous with “sinistral fault.”

lens. A sedimentary deposit characterized by converging surfaces, thick in the middle and thinning out toward the edges, resembling a convex lens.

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

lithic. A sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

lithification. The conversion of sediment into solid rock.

lithify. To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through compaction and cementation.

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

lithosphere. The relatively rigid outmost shell of Earth’s structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

magma. Molten rock beneath Earth’s surface capable of intrusion and extrusion.

magma reservoir. A chamber in the shallow part of the lithosphere from which volcanic materials are derived; the magma has ascended from a deeper source.

magmatic arc. Zone of plutons or volcanic rocks formed at a convergent boundary.

mantle. The zone of Earth’s interior between the crust and core.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with “physical weathering.”

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

monzonite. A group of plutonic (intrusive igneous) rocks of intermediate color containing approximately equal amounts of alkali feldspar and plagioclase, little or no quartz, and commonly augite as the main mafic mineral. Intrusive equivalent of latite.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

oblique fault. A fault in which motion includes both dip-slip and strike-slip components (also see “dip-slip fault” and “strike-slip fault”).

oceanic crust. Earth’s crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

orogeny. A mountain-building event.

outcrop. Any part of a rock mass or formation that is exposed or “crops out” at Earth’s surface.

paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.

Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.

parent material. Geologic material from which soils form.

passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").

pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

pediment. A gently sloping, erosional bedrock surface at the foot of mountains or plateau escarpments.

perthite. A variety of feldspar consisting of parallel or subparallel intergrowths in which the potassium-rich phase (usually microcline) appears to be the host from which the sodium-rich phase (usually albite) separated at a critical temperature.

phenocryst. A coarse (large) crystal in a porphyritic igneous rock.

piedmont. An area, plain, slope, glacier, or other feature at the base of a mountain.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.

pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.

porphyritic. Describes an igneous rock wherein the rock contains conspicuously large crystals in a fine-grained groundmass.

potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

pull-apart basin. A topographic depression created by an extensional bend or extensional overstep along a strike-slip fault.

pyroclast. An individual particle ejected during a volcanic eruption.

pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.

pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.

quartzite. Metamorphosed quartz sandstone.

quartz monzonite. A plutonic rock with quartz between 5% and 20% and alkali feldspar/total feldspar ratio between 35% and 65%. Intrusive equivalent of rhyodacite.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

regression. A long-term seaward retreat of the shoreline or relative fall of sea level.

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

rhyodacite. A volcanic rock intermediate between rhyolite and dacite. Extrusive equivalent to quartz monzonite.

rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

rift. A region of crust where extension results in formation of many related normal faults, often associated with volcanic activity.

rift valley. A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

rock. A solid, cohesive aggregate of one or more minerals.

rock fall. Mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sandstone. Clastic sedimentary rock of predominantly sand-sized grains.

schist. A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.

seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

sheetwash (sheet erosion). The removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land by broad continuous sheets of running water rather than by streams flowing in well-defined channels.

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

silicic. Describes a silica-rich igneous rock or magma.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

sphene. A usually yellow or brown mineral occurring as an accessory mineral in granitic rocks and in calcium-rich metamorphic rocks. Also called "titanite."

spreading center. A divergent boundary where two lithospheric plates are spreading apart. It is a source of new crustal material.

stock. An igneous intrusion exposed at the surface; less than 100 km^2 (40 mi^2) in size. Compare to "pluton."

strata. Tabular or sheet-like masses or distinct layers of rock.

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

stream terrace. Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.

tectonic. Relating to large-scale movement and deformation of Earth's crust.

terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").

terrane. A large region or group of rocks with similar geology, age, or structural style.

terrestrial. Relating to land, Earth, or its inhabitants.

terrigenous. Derived from the land or a continent.

thalweg. The line connecting the lowest or deepest points along a stream bed; the line of maximum depth.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

transform fault. A strike-slip fault that links two other faults or two other plate boundaries (e.g. two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

trend. The direction or azimuth of elongation of a linear geologic feature.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

tuffaceous. A non-volcanic, clastic sedimentary rock that contains mixtures of ash-size pyroclasts.

type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

vitric. Describes pyroclastic material that is characteristically glassy.

vitrophyre. Any porphyritic igneous rock having a glassy groundmass.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

weathering. The physical, chemical, and biological processes by which rock is broken down.

Literature Cited

This section lists references cited in this report. A more complete geologic bibliography is available from the National Park Service Geologic Resources Division.

Allison, L. 2010. "Y-crack" earth fissure re-opens near Queen Creek. Arizona Geology: blog of the State Geologist of Arizona. (http://arizonageology.blogspot.com/2010/02/y-crack-earth-fissure-re-opens-near.html). Accessed July 1, 2010.

Allison, M. L. and T. C. Shipman. 2007. Earth Fissure Mapping Program: 2006 Progress Report. Open-file Report 07-01. Arizona Geological Survey, Tucson, AZ, USA. (http://www.azgs.state.az.us/efmaps.shtml). Accessed June 12, 2010.

Anderson, J. L. 1988a. Core complexes of the Mojave-Sonoran Desert: Conditions of plutonism, mylonitization, and decompression. Pages 502-525 in W. G. Ernst, editor. Metamorphism and crustal evolution of the western United States. Prentice Hall, Englewood Cliffs, New Jersey, USA.

Anderson, S. R. 1988b. Potential for aquifer compaction, land subsidence, and earth fissures in the Tucson basin, Pima County, Arizona. U. S. Geological Survey hydrologic Investigations Atlas HA-713 (scale 1:250,000).

Anderson, T. H., and J. A. Nourse. 2005. Pull-apart basins at releasing bends of the sinistral Late Jurassic Mojave-Sonora fault system. Special Paper 393. Geological Society of America, Boulder, Colorado, USA.

Anderson, T. H., and L. T. Silver. 2005. The Mojave-Sonora megashear; field and analytical studies leading to the conception and evolution of the hypothesis. Special Paper 393. Geological Society of America, Boulder, Colorado, USA.

Arizona Department of Environmental Quality. 2010. Arizona climate change initiatives. (http://www.azclimatechange.gov). Accessed June 12, 2010.

Arizona Earthquake Information Center. 2009. Ground shaking and earthquake damage in Arizona (1887-1999). (http://www4.nau.edu/geology/aeic/eq_fault_maps.html). Accessed June 12, 2010.

Arizona Geological Survey Earth Fissure Center. 2006. What are earth fissures? (http://www.azgs.state.az.us/EFC.shtml). Accessed June 12, 2010.

Arizona Land Subsidence Group. 2007. Land subsidence and earth fissures in Arizona. Contributed Report CR-07-C. Arizona Geological Survey, Tucson, AZ, USA. (http://www.azgs.state.az.us/Resources/CR-07-C_Dec07.pdf). Accessed June 12, 2010.

Arizona State Museum. 2010. Arizona through time: Southern Arizona culture history. (http://www.statemuseum.arizona.edu/exhibits/blm_vignettes/history_trincheras.shtml). Accessed March 29, 2010.

Betancourt, J. 1990. Tucson's Santa Cruz River and the arroyo legacy. Dissertation. University of Arizona, Tucson, Arizona, USA.

Bilodeau, W. L., C. F. Kluth, and L. K. Vedder. 1987. Regional stratigraphic, sedimentologic and tectonic relationships of the Glance Conglomerate in southeastern Arizona. Pages 229-256 in W. R. Dickinson and M. A. Klute, editors. Mesozoic rocks of southern Arizona and adjacent areas. Digest 18. Arizona Geological Society, Tucson, Arizona, USA.

Blakey, R. C. 1980. Pennsylvanian and Early Permian paleogeography, southern Colorado Plateau and vicinity. Pages 239-258 in T. D. Fouch and E. R. Magathan, editors. Paleozoic paleogeography of west-central United States. Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Denver, Colorado, USA.

Christiansen, E. II, B. J. Kowallis, and M. D. Barton. 1994. Temporal and spatial distribution of volcanic ash in Mesozoic sedimentary rocks of the Western Interior: An alternative record of Mesozoic magmatism. Pages 73-94 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region, USA. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado, USA.

Coney, P. J. 1979. Tertiary evolution of Cordilleran metamorphic core complexes. Pages 14-28 in J. M. Armentrout, M. R. Cole, and H. Terbest, Jr., editors. Cenozoic paleogeography of the western United States. Pacific Section, Society of Economic Paleontologists and Mineralogists, Los Angeles, California, USA.

Conway, C. M. and L. T. Silver. 1989. Early Proterozoic rocks (1710 – 1615 Ma) in central to southeastern Arizona. Pages 165-186 in J. P. Jenny and S. J. Reynolds, editors. Geologic evolution of Arizona. Digest 17. Arizona Geological Society, Tucson, Arizona, USA.

Davis, G. H. 1987. Saguaro National Monument, Arizona: Outstanding display of the structural characteristics of metamorphic core complexes. Pages 35-40 in M. L. Hill, editor. Cordilleran Section of the Geological Society of America. Centennial Field Guide

1, Geological Society of America, Boulder, Colorado, USA.

Dickinson, W. R. 1979. Cenozoic plate tectonic setting of the Cordilleran region in the United States. Pages 1-13 in J. M. Armentrout, M. R. Cole, and H. Terbest, Jr, editors. Cenozoic paleogeography of the western United States. Pacific Section, Society of Economic Paleontologists and Mineralogists, Los Angeles, California, USA.

Dickinson, W. R. 1991. Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona. Special Paper 264. Geological Society of America, Boulder, Colorado, USA.

Dickinson, W. R., and T. F. Lawton. 2001. Tectonic setting and sandstone petrofacies of the Bisbee Basin (USA-Mexico). Journal of South American Earth Sciences 14 (5): 474-504.

Drewes, H. 1968. New and revised stratigraphic names in the Santa Rita Mountains of southeastern Arizona. Bulletin 1274-C. U.S. Geological Survey, Reston, VA, USA.

Drewes, H. 1980. Tectonic map of southeast Arizona (scale 1:125,000). Miscellaneous Investigations Map I-1109. U.S. Geological Survey, Reston, VA, USA.

Drewes, H. 1981. Geologic map and sections of the Bowie Mountain South quadrangle, Cochise County, Arizona (scale 1:24,000). Miscellaneous Investigations Series Map I-1363. U.S. Geological Survey, Reston, VA, USA.

Drewes, H. 1982. Geologic map and sections of the Cochise Head quadrangle and adjacent areas, Southeastern Arizona (scale 1:24,000). Miscellaneous Investigations Series Map I-1312. U.S. Geological Survey, Reston, VA, USA.

Dubiel, R. F. 1994. Triassic deposystems, paleogeography, and paleoclimate of the Western Interior. Pages 133-168 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado, USA.

DuBois, S. M. and A. W. Smith 1980. The 1887 earthquake in San Bernardino Valley, Sonora—Historical accounts and intensity patterns in Arizona. Arizona Bureau of Geology and Mineral Technology, Phoenix, AZ, USA. Special Paper 3.

Elder, W. P., and J. I. Kirkland. 1994. Cretaceous paleogeography of the southern Western Interior Region. Pages 415-440 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado, USA.

Gelt, J. 1992. Land subsidence, earth fissures change Arizona's landscape. The University of Arizona Water Resources Research Center. (http://ag.arizona.edu/azwater/arroyo/062land.html). Accessed June 12, 2010.

Graham, J. 2009. Chiricahua National Monument Geologic Resources Inventory Report. Natural Resource Report NPS/NRPC/GRD/NRR—2009/081. National Park Service, Denver, Colorado. (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm). Accessed 15 August 2011.

Graham, J. 2010. Saguaro National Park: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/233. National Park Service, Ft. Collins, Colorado. (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.) Accessed 15 August 2011.

Graham, J. 2011. Coronado National Memorial: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2011/438. National Park Service, Ft. Collins, Colorado. (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm). Accessed 1 September 2011.

Graham, J. in prep. (2011). Fort Bowie National Historic Site: geologic resources inventory report. Submitted to Natural Resource Report NPS/NRPC/GRD/NRR series. National Park Service, Ft. Collins, Colorado.

Haenggi, W. T., and W. R. Muehlberger. 2005. Chihuahua Trough; a Jurassic pull-apart basin. Special Paper 393. Geological Society of America, Boulder, Colorado, USA.

Hoffman, P. F. 1989. Precambrian geology and tectonic history of North America. Pages 447-512 in A. W. Bally and A. R. Palmer, editors. The geology of North America: An overview. The Geology of North America-A, Geological Society of America, Boulder, Colorado, USA.

International Boundary and Water Commission. 2010. Nogales field office and Wastewater Treatment Plant (NIWTP). (http://www.ibwc.state.gov/Organization/Operations/Field_Offices/Nogales.html). Accessed March 30, 2010.

Karl, T. R., J. M. Melillo, and T. C. Peterson, editors. 2009. Global climate change impacts in the United States. Cambridge University Press. (http://www.globalchange.gov/usimpacts). Access June 12, 2010.

Kauffman, E. G., 1977, Geological and biological overview: Western Interior Cretaceous basin. Mountain Geologist 14: 75-99.

Kluth, C. F. 1983. Geology of the northern Canelo Hills and implications for the Mesozoic tectonics of southeastern Arizona. Pages 159-171 in M. W. Reynolds and E. D. Dolly, editors. Mesozoic paleogeography of west-central United States. Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Denver, Colorado, USA.

Kring, D. A. 2002. Desert heat – volcanic fire: The geologic history of the Tucson Mountains and southern Arizona. Digest 21. Arizona Geological Society, Tucson, Arizona, USA.

Lawton, T. F. 1994. Tectonic setting of Mesozoic sedimentary basins, Rocky Mountain region, United States. Pages 1-26 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado, USA.

Lillie, R. J. 2005. Parks and plates: The geology of our national parks, monuments, and seashores. W.W. Norton and Company, New York, New York, USA.

Lipman, P. W. and J. T. Hagstrum. 1992. Jurassic ash-flow sheets, calderas, and related intrusions of the Cordilleran volcanic arc in southeastern Arizona: Implications for regional tectonics and ore deposits. Geological Society of America Bulletin 104: 32-39.

McGarvin, T. G. 1987. The 1887 Sonoran Earthquake: It wasn't our fault. Arizona Bureau of Geology and Mineral Technology Fieldnotes 17(2). (http://www.azgs.az.gov/Hazards_ocr/earthquakes/1887SonoranEarthquakeNotOurFault.pdf). Accessed 25 August 2011.

Menges, C. M. and P. A. Pearthree. 1989. Late Cenozoic tectonism in Arizona and its impact on regional landscape evolution. Pages 649-680 in J. P. Jenny and S. J. Reynolds, editors. Geologic evolution of Arizona. Digest 17. Arizona Geological Society, Tucson, Arizona, USA.

Morrison, R. B. 1991. Quaternary geology of the southern Basin and Range province. Pages 353-373 in R. B. Morrison, editor. Quaternary nonglacial geology: Conterminous U.S. The Geology of North America, K-2, Geological Society of America, Boulder, Colorado, USA.

National Weather Service. 2010. Top 10 weather/water/climate stories to impact the Tucson metro area during the 20th century. (http://www.wrh.noaa.gov/twc/climate/20thcentury_top10wx.php). Accessed April 2, 2010.

Nations, D., J. C. Wilt, and R. H. Hevly. 1985. Cenozoic paleogeography of Arizona. Pages 335-356 in R. M. Flores and S. S. Kaplan, editors. Cenozoic paleogeography of west-central United States. Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Denver, Colorado, USA.

National Park Service. 2003. Baseline water quality data inventory and analysis: Tumacácori National Historical Park. Technical Report NPS/ NRWRD/ NRTR-2001/284. U. S. Department of the Interior, Washington, D.C. (http://nrdata.nps.gov/tuma/nrdata/water/baseline_wq/docs/TUMAWQAA.pdf). Accessed March 30, 2010).

National Park Service. 2006a. History and culture. (http://www.nps.gov/tuma/historyculture/index.htm). Accessed March 23, 2010.

National Park Service 2006b. Soil Survey Geographic Database (SSURGO) for Tumacácori National Historical Park. NPS Inventory and Monitoring Program, Soil Resources Inventory. Ft. Collins, Colorado, USA. (https://nrinfo.nps.gov/Reference.mvc/Profile?Code=1048987). Accessed 25 August 2011.

National Park Service. 2007. The Santa Cruz River. (http://www.nps.gov/tuma/naturescience/scriver.htm). Accessed June 10, 2010.

National Park Service. 2010a. Natural features and ecosystems. (http://www.nps.gov/tuma/naturescience/naturalfeaturesandecosystems.htm) Accessed June 10, 2010.

National Park Service. 2010b. Mapping protocols planned for implementation in SODN parks. (http://science.nature.nps.gov/im/units/sodn/protocols_by_park.cfm). Accessed June 12, 2010.

National Park Service. 2010c. Climate change. SODN climate change protocols. (http://www.nature.nps.gov/climatechange/aridlands.cfm). Accessed June 12, 2010.

Oldow, J. S., A. W. Bally, H. G. Avé Lallemant, and W. P. Leeman. 1989. Phanerozoic evolution of the North American Cordillera; United States and Canada. Pages 139-232 in A. W. Bally and A. R. Palmer, editors. The geology of North America: An overview. The Geology of North America-A, Geological Society of America, Boulder, Colorado, USA.

Pallister, J. S., E. A. du Bray, and D. B. Hall. 1997. Guide to the volcanic geology of Chiricahua National Monument and vicinity, Cochise County, Arizona. Pamphlet to accompany the Miscellaneous Investigations Series Map I-2541. U.S. Geological Survey, Reston, Virginia, USA.

Pearthree, P. A. and S. S. Calvo. 1987. The Santa Rita fault zone: Evidence for large magnitude earthquakes with very long recurrence intervals, Basin and Range province of southeastern Arizona. Bulletin of the Seismological Society of America 77: 97-116.

Peterson, J. A. 1980. Permian paleogeography and sedimentary provinces, west central United States. Pages 271-292 in T. D. Fouch and E. R. Magathan, editors. Paleozoic paleogeography of west-central United States. Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Denver, Colorado, USA.

Peterson, F. 1994. Sand dunes, sabkhas, streams, and shallow seas: Jurassic paleogeography in the southern part of the Western Interior Basin. Pages 233-272 in M. V. Caputo, J. A. Peterson, and K. J. Franczyk, editors. Mesozoic systems of the Rocky Mountain region. Rocky Mountain Section, Society for Sedimentary Geology, Denver, Colorado, USA.

Ruth, C. W. 2009. Stormwater planning issues for the Ambos Nogales region. (http://www.epa.gov/ocem/gneb/pdf/2009_gneb_ruth.pdf). Accessed March 30, 2010).

Short, N. M., Sr. 2010. The Nevada Basin and Range, the desert southwest, northern Rocky Mountains, the Snake River Plains and Columbia Plateau. National Aeronautics and Space Administration (NASA) Remote Sensing Tutorial. (http://rst.gsfc.nasa.gov/Sect6/Sect6_8.html). Accessed July 2, 2010.

Simons. F. S. 1974. Geologic map and sections of the Nogales and Lochiel quadrangles, Santa Cruz County, Arizona. Miscellaneous Investigations Map I-762 (scale 1:48,000). U. S. Geological Survey, Reston, VA, USA.

Spencer, J. E. and S. J. Reynolds. 1989. Middle Tertiary tectonics of Arizona and adjacent areas. Pages 539-574 in J. P. Jenny and S. J. Reynolds, editors. Geologic evolution of Arizona. Digest 17. Arizona Geological Society, Tucson, Arizona, USA.

Sumner, J. R. 1977. The Sonora earthquake of 1887. Bulletin of the Seismological Society of America 67 (4): 1219-1223.

Stevens, C. H., P. Stone, and J. S. Miller. 2005. A new reconstruction of the Paleozoic continental margin of southwestern North America; implications for the nature and timing of continental truncation and the possible role of the Mojave-Sonora megashear. Special Paper 393. Geological Society of America, Boulder, Colorado, USA.

Tempe History Museum. 2010. The Hohokam. (http://www.tempe.gov/museum/Tempe_history/basics/hohokam.htm). Accessed March 29, 2010

Tosdal, R. M., G. B. Haxel, and J. E. Wright. 1989. Jurassic geology of the Sonoran Desert region, southern Arizona, southeastern California, and northernmost Sonora: Construction of a continental-margin magmatic arc. Pages 397-434 in J. P. Jenny and S. J. Reynolds, editors. Geologic evolution of Arizona. Digest 17. Arizona Geological Society, Tucson, Arizona, USA.

Tweet, J. S., V. L. Santucci, and J. P. Kenworthy. 2008. Paleontological resource inventory and monitoring Sonoran Desert Network: Tumacácori National Historical Park. Natural Resource Technical Report NPS/NRPC/NRTR 2008/130. National Park Service, Natural Resource Program Center, Fort Collins, CO, USA.

Environmental Protection Agency (EPA). 2009. U.S. EPA celebrates opening of Nogales International Wastewater Treatment Plant (http://yosemite.epa.gov/opa/admpress.nsf/d985312f6895893b852574ac005f1e40/30969e22ffbbb1a3852575df0071edf1!OpenDocument). Accessed March 30, 2010.

U.S. Geological Survey. 2000. Land subsidence in the United States. (http://water.usgs.gov/ogw/pubs/fs00165/SubsidenceFS.v7.pdf). Accessed June 12, 2010.

U.S. Geological Survey. 2010. Groundwater depletion. (http://ga.water.usgs.gov/edu/gwdepletion.html). Accessed July 1, 2010.

U.S. Geological Survey. 2009. Arizona: Earthquake history. Earthquake Hazards Program, Golden, CO, USA (http://earthquake.usgs.gov/earthquakes/states/arizona/history.php). Accessed April 1, 2010.

Vandervoet, K. 2006. Recent flooding in Tubac, Amado, Tumacácori has residents frustrated. (http://www.nogalesinternational.com/articles/2006/09/05/news/news5.txt). Accessed 31 March 2010.

Webb R. H. and J. L. Betancourt. 1992. Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona. Water-Supply Paper 2379. U. S. Geological Survey, Washington, D.C., USA.

Youberg, A. and W. R. Helmick. 2001. Surficial geology and geologic hazards of the Amado-Tubac area, Santa Cruz and Pima Counties, Arizona. Arizona Geological Survey Digital Geologic Map 13 (DGM-13) (scale 1:24,000).

Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of June 2011.

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado). http://nature.nps.gov/geology/

NPS Geologic Resources Inventory. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

Harris, A. G., E. Tuttle, and S. D. Tuttle. 2003. Geology of National Parks. Sixth Edition. Kendall/Hunt Publishing Co., Dubuque, Iowa, USA.

Kiver, E. P. and D. V. Harris. 1999. Geology of U.S. parklands. John Wiley and Sons, Inc., New York, New York, USA.

Lillie, R. J. 2005. Parks and Plates: The geology of our national parks, monuments, and seashores. W.W. Norton and Co., New York, New York, USA. [Geared for interpreters].

NPS Geoscientist-in-the-parks (GIP) internship and guest scientist program. http://www.nature.nps.gov/geology/gip/index.cfm

Resource Management/Legislation Documents

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual
R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (Denver, repository for technical (TIC) documents): http://etic.nps.gov/

Geological Survey and SocietyWebsites

Arizona Geological Survey: http://www.azgs.state.az.us/

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

Other Geology/Resource Management Tools

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd Edition). Bantam Doubleday Dell Publishing Group, New York.

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”).

U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.er.usgs.gov

U.S. Geological Survey, description of physiographic provinces: http://tapestry.usgs.gov/Default.html

Appendix: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Tumacácori National Historical Park, held on April 4, 2006. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Name	Affiliation	Position	Phone	E-mail
Allison, Lee	Geologist	Arizona Geological Survey	520-770-3500	lee.allison@azgs.az.gov
Casavant, Bob	Research & Science Manager	Arizona State Parks	520-626-3785	casavant@geo.arizona.edu
Covington, Sid	Geologist	NPS GRD	303-969-2154	sid_covington@nps.gov
Graham, John	Geologist	Colorado State University		
Hubbard, Andy	Network coordinator	NPS Sonoran Desert Network	520-546-1607 ext. 1	andy_hubbard@nps.gov
Kerbo, Ron	Cave specialist	NPS GRD	303-969-2097	Ron_Kerbo@nps.gov
Moss, Jeremy	Archeologist	NPS Tumacácori National Historical Park	520-398-2341 ext. 38	jeremy_moss@nps.gov
O'Meara, Stephanie	Geologist	Colorado State University	970-225-3584	Stephanie_O'Meara@partner.nps.gov
Pearthree, Phil	Geologist	Arizona Geological Survey	520-770-3500	phil.pearthree@azgs.az.gov
Spencer, Jon	Geologist	Arizona Geological Survey	520-770-3500	jon.spencer@azgs.az.gov
Swann, Don	Biologist	NPS Saguaro National Park	520-733-5177	don_swann@nps.gov
Weesner, Meg	Chief, Science and Resource Management	NPS Saguaro National Park	520-733-5170	meg_weesner@nps.gov

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 311/109539, August 2011

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov