TEN

Geologic Origin of the Sonoran Desert

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CONCEPTS OF GEOLOGIC time and space challenge the human imagination. We tend to think in terms of lifetimes, or centuries. What can 10,000 years possibly mean to us, let alone 65,000 or 70 million? Place, in geologic terms, is an equally difficult notion. Though we may imagine different landforms and different vegetation in the distant past, we probably still imagine "here" as a permanent spot on the globe. But geology and time mock our notion of permanence. Geology deals with continents that break apart, drift, collide and re-form or slide beneath one another, with rivers and oceans that appear and disappear, with mountain ranges whose battered remnants have been carried away and now lie buried on some other continent. Geology asks us to imagine endless transformation and impermanence as we consider Earth's history. Arizona once sat near 80° south latitude, and has also basked near the humid equator.

But geology, the study and interpretation of Earth's history, encompasses much more than the study of sterile rock masses and drifting continents. The land, the oceans, the climate, our atmosphere, and all life have coevolved on this planet in a complex, interwoven web. Geologic and climatic changes have always occurred, and all life-forms must adapt to these changes or perish. There are many ways that the Earth's changes influence local ecosystems. The least obvious is slow continental drifting of landmasses across lines of latitude and longitude, which affects oceanic and atmospheric circulation, storm tracks, climate, and the timing and duration of seasons. These drifting landmasses are called *tectonic plates* (or *lithospheric plates*), and they are great slabs of the Earth's crust along with the outermost mantle beneath it. Like moving jigsaw-puzzle pieces, these plates move slowly across the Earth (several inches per year). Continents eventually collide, usually with one plate being forced beneath the other and resulting in the upthrust of mountain chains. Massive volcanic activity occurs where oceanic crust on one plate slides beneath another plate, as with the Andes Mountains in modern times. There are eight major plates, and many minor plates, in constant relative motion on the Earth, and they have apparently been in motion since the Earth's crust solidified about 4 billion years ago.

When mountains take form, complex layered biotic communities, or biomes, develop along their slopes. In southeastern Arizona, the higher mountains exhibit nearly 2 miles (3.2 km) of vertical relief, from desert valleys to mountaintops exceeding 9000 feet (2745 m) in elevation. These high ranges—such as the Santa Catalina, Chiricahua, Santa Rita, and Pinaleño Mountains—harbor oak woodlands, pine forests, and even subalpine spruce-fir conifer forests. Because these ranges are surrounded by valleys of desertscrub or desert grassland, they are called "Sky Islands" (see chapter 3).

As climates and habitats change, plant and animal species either adapt, migrate to more favorable ground, or go extinct. Migratory routes are often determined by geologic processes. For example, climate dictates whether a river is perennial or intermittent, and whether a lake expands or dries up. New mountains produce new rivers and change the courses of old rivers. These changes may block or enhance migration for terrestrial animals, while simultaneously creating barriers or corridors for aquatic species.

Ancient life even affected later geologic and climatic conditions. Biologically produced gases (oxygen, carbon dioxide, methane, nitrous oxide) maintain a chemically reactive atmosphere that in turn influences rates of rock weathering, the nature of sedimentary deposits, and the content of gases in the atmosphere. Desert soils—highly variable in their water-holding capability, salinity, and alkalinity—strongly influence the kinds of plants that will survive on them. Some desert plants, for example, are well adapted to soils that would be toxic to other plants (see chapter 11).

Ancient Arizona

In the PALEOZOIC ERA (541–252 mya), our western mountainous North America did not yet exist. North America was slowly drifting northward across the equator and the West was mostly flat, largely inundated by the sea, and accumulating thick deposits of sediments from oceanic plankton whose dead skeletons rained down on the seafloor. Today, remains of these marine planktonic sediment layers can be seen in an exposed 4000-foot-thick (1220 m) Paleozoic limestone layer in the Whetstone Mountains east of Tucson, and in the beautiful Kartchner Caverns, which are dissolved out of this same limestone bed. But the flat seafloor nature of Paleozoic marine layering is best seen in the Grand Canyon and Colorado Plateau, a huge geological province that largely escaped the tumultuous, post-Paleozoic mountain-building events in western North America, except that the plateau has been uplifted thousands of feet.

By the early MESOZOIC ERA (252–65.5 mya), North America had drifted north of the equator, all land above sea level had coalesced into a "supercontinent" known as Pangaea, and the vast epicontinental seas of the Paleozoic were receding. North America sat on the western border of Pangaea, between the equator and 60° north latitude. The Mesozoic was generally a time of warm, moist climates for Pangaea.

Mesozoic fossil beds are abundant in the Southwest. Fossil records from the Tucson and Santa Rita Mountains and surrounding floodplains contain abundant evidence of a rich ecological system from the Jurassic through the Late Cretaceous (150–90 mya), where, over time, a diversity of terrestrial and marine animals, from dinosaurs to mammals, roamed floodplains, lakeshores, and ancient forests (see "The Sonoran Desert Fossil Legacy" sidebar on page 73).

As Pangaea began to break apart, the Atlantic Ocean opened, separating North and South America from Africa and Eurasia. As this new sea widened, ocean circulation and global climates changed dramatically. The opening of the Atlantic Ocean pushed North and South America to the west, and in time the west coast of North America encountered an oceanic plate called the Farallon Plate. The lighter North

The Sonoran Desert Fossil Legacy

Life's long drama is abundantly preserved in the rock record of the Sonoran Desert Region. The oldest stratified rocks of the Sonoran Desert, dating from 1.8 to 1.2 billion years ago, contain a few traces of small mushroom-shaped colonies of bacteria that once grew in protected aquatic habitats, as well as colonies of heat-loving bacteria that lived in extreme hot-spring environments.

Paleozoic shales and limestones (541–252 mya) contain occasional remains of trilobites, shark and fish teeth, crinoids, corals, bryozoans, conodonts, clams, brachiopods, oysters, and a variety of cephalopods (a class of molluscs that also includes octopus and squid). Scientists envision their marine environment as shallow tropical ocean waters with coral reefs, lagoons, and inlets, reminiscent of the Bahamas-Florida-Mississippi Delta region.

Mesozoic fossil beds (150–90 mya) represent a regional trend toward terrestrial conditions as the land rose and drained. River floodplain deposits of Jurassic or Cretaceous age in the Tucson and Galiuro Mountains contain tracks of lizards found with rare fossils of horsetails (*Equisetum* spp.) and petrified wood. Cretaceous beds contain clams, sharks, marine reptiles like the mosasaur (an aquatic monitor lizard), and turtles. Cretaceous low-elevation coniferous forests were resplendent with cycad and ginkgo trees, through which glided flying reptiles. Late Cretaceous strata of the northern Santa Rita Mountains contain a remarkable fossil record that includes the titanic long-necked sauropods, horned and duckbill dinosaurs, and some of Arizona's oldest fossil mammals. They all lived along large river floodplains and shores of ancient inland lakes, sharing territories with crocodiles and lizards.

Cenozoic deposits contain a mammal-dominated fauna that inhabited a land reminiscent of a lush East African savanna. Earlier forms included ancestral horses, giant rhino-like titanotheres, and oreodonts (ancestors to peccaries and camels). By the late Miocene and Pliocene (10–2 mya) grasses and grazers became widespread. Pleistocene fauna of the last 2.6 million years included camels, herds of bison and near-modern horses, mastodons, imperial mammoths, giant ground sloths, wolves, lions, giant beavers, and short-faced bears. North America's first people left spearpoints imbedded in fossil remains of some of these animals at sites near former springs. The modern Sonoran Desert ecosystem seems a distant cousin to the ancient environments of the region.

American Plate overrode the heavier Farallon Plate, and this subduction caused the creation of great western mountain ranges by way of uplift and volcanic eruptions. The two largest of these ranges were the Rocky Mountains of the United States and Canada and the Sierra Madre Occidental of Mexico. Today, these two ranges run from northern Alaska to southern Mexico, a distance of 4500 miles (7200 km), about the same length as the Andes in South America (also created by subduction, in the southern Pacific). The Rockies and Sierra Madre form the North American Cordillera (or Western Cordillera), sometimes called the "spine of the continent." Where these two great ranges meet, in southeastern Arizona and northeastern Sonora, there is a region of lower elevation called the Cordilleran Gap punctuated with mountain ranges. In historic times, the valleys of the Cordilleran Gap, only 4000 to 5000 feet (1220–1525 m) in elevation, were a key passageway for people from the Midwest and East emigrating to Arizona; the Union Pacific Railroad was built through this gap, and today Interstate 10 runs through this low-lying land. But the Cordilleran Gap has also played an important role in the ecology of the region, as we describe below.

The CENOZOIC ERA (65.5 mya to the present) has been an era of rapidly changing landmasses and climates, as Pangaea's continued fragmentation altered ocean and atmospheric (wind) currents. At the beginning of the Cenozoic, North and South America separated from each other, creating a seaway between the Atlantic and Pacific Oceans that lasted around

50 million years before it was again closed by new plate movements. Also during this time, South America decoupled from Antarctica (about 50 mya) and the Drake Passage opened to initiate circumpolar currents, profoundly changing the thermal regime of the world's oceans. Africa collided with Asia (about 25 mya), separating the Mediterranean Sea from the Indian Ocean and breaking up the once-circumtropical Tethys Sea, and later India collided with Asia to initiate the rise of the great Himalaya Mountains. During the past 2.6 million years (the Quaternary period), a repeating series of glacial episodes ("ice ages") and interglacial periods have had profound effects on the plant and animal distributions of the Southwest and much of the world.

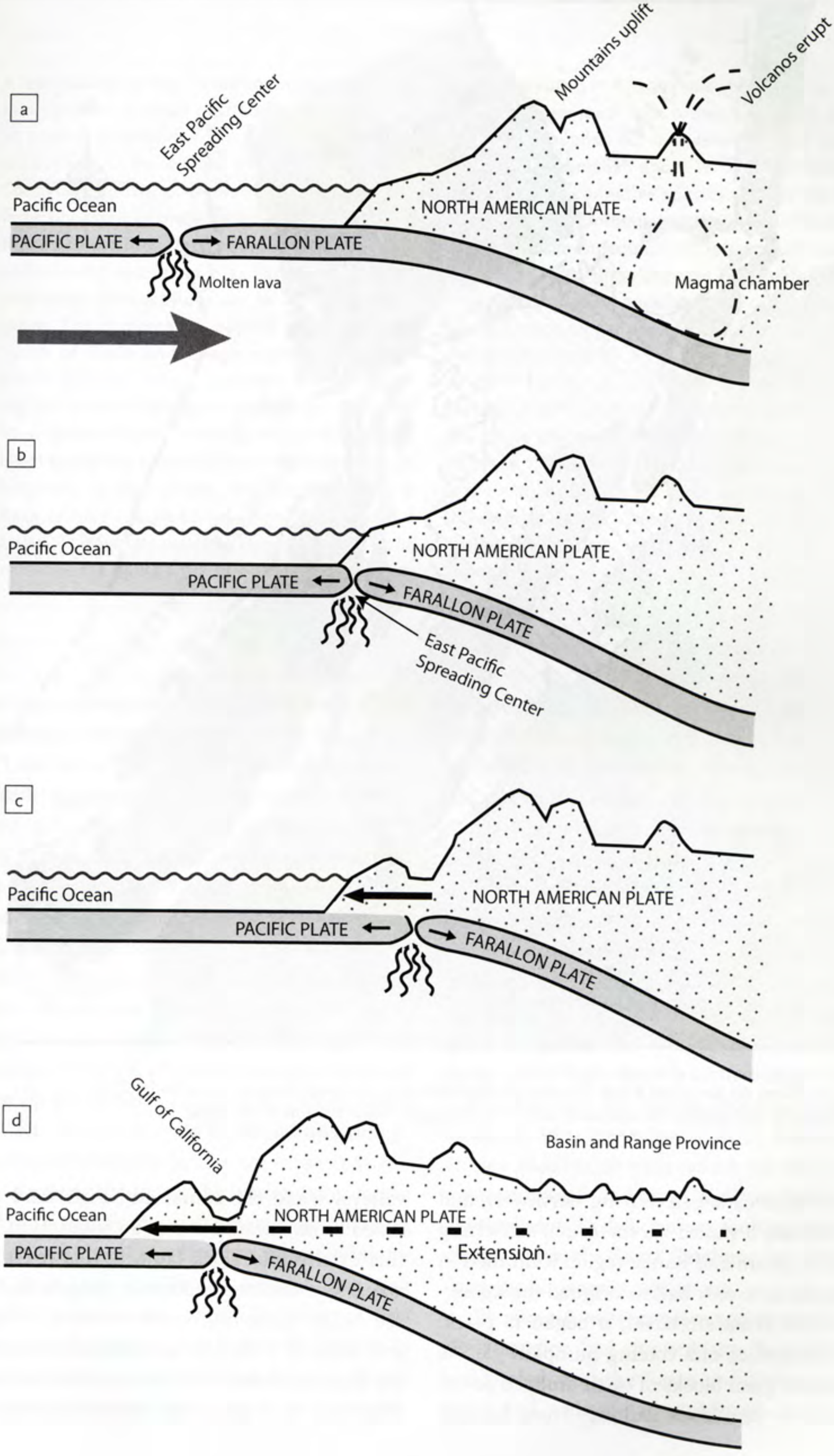
This deep geological history finds expression in the Sonoran Desert's exposed rock formations, fossil beds, modern mountain ranges, and contemporary plant and animal distributions. It was largely during the late Mesozoic and the Cenozoic era that the modern Southwestern landscape evolved, including the Rocky Mountains, Mexico's Sierra Madre Occidental, the coastal ranges and Sierra Nevada of the West Coast, and the Basin and Range Province, the geological province in which the Sonoran Desert resides.

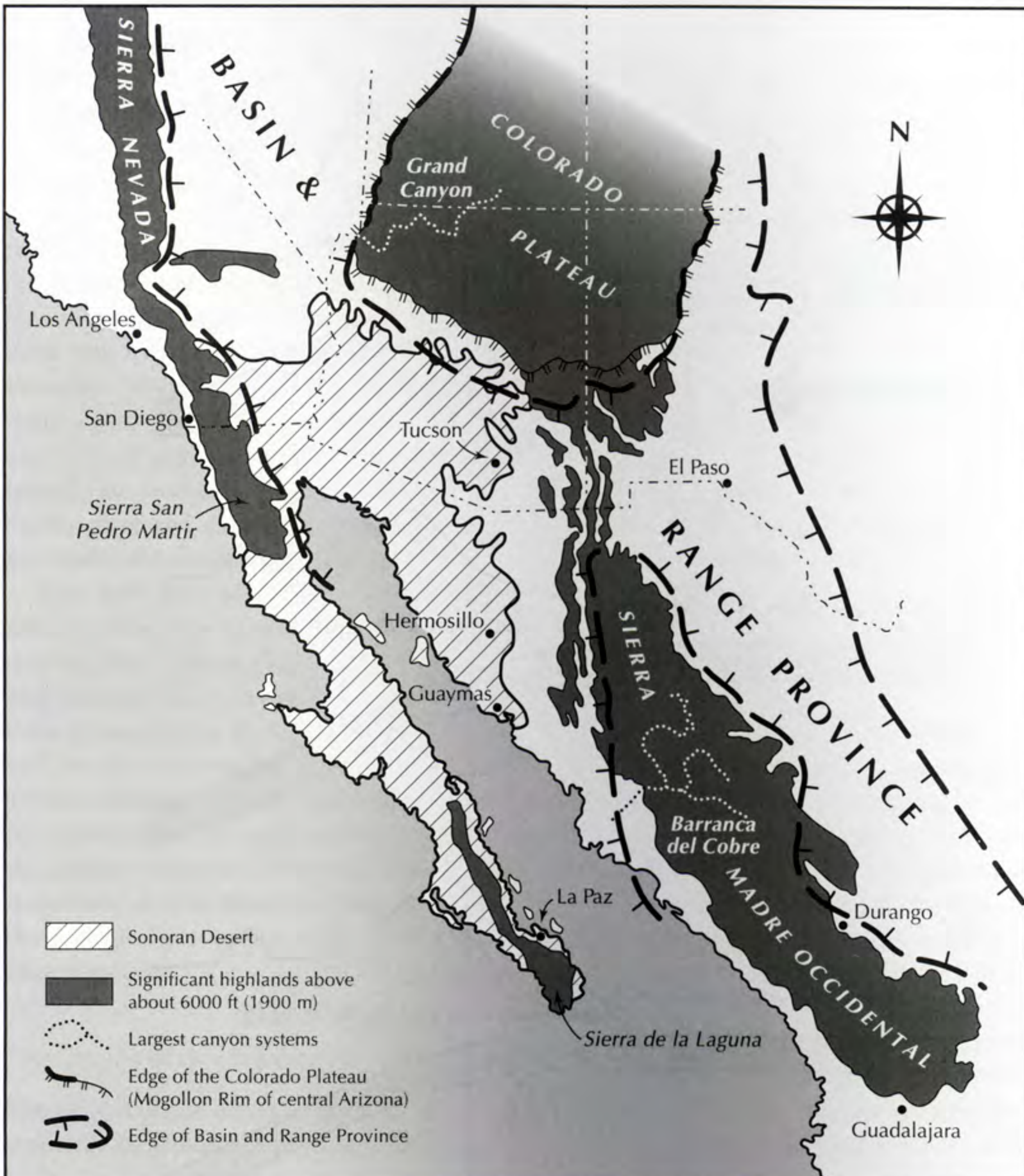
The Origins of Our Mountainous West

The origins of our current Southwestern landscape can be thought of as a two-step process, each of which wreaked havoc on the Earth's crust. First came crustal compression, and later, crustal extension. Crustal compression was the result of friction as the oceanic Farallon Plate was subducted beneath the North American Plate, beginning in the Mesozoic and continuing into the middle to late Cenozoic. The displacement of the Farallon Plate eastward beneath the western coast of North America pushed (compressed) the crust of the continent, forcing it into wrinkles like a rug pushed against a wall. The submergence also melted basement rocks and created massive volcanic events throughout the region. The result was the creation of many familiar mountain ranges, including the Rocky Mountains (mostly wrinkles) and Sierra Madre Occidental (mostly volcanic rocks) in Mexico. This mountain-building event, called the Laramide Orogeny, continued until approximately 50 million years ago.

Around 45 million years ago, the East Pacific Rise (a spreading center beneath the Pacific Ocean that had been pushing the Farallon Plate eastward) was overridden by the westward-drifting North American Plate. (A *spreading center* is the place where two plates are spreading apart as magma rises to the surface and cools between them.) When that happened, western Mexico (now the Baja California Peninsula) and Southern California (west of the San Andreas fault) separated from North America and attached to the Pacific Plate, west of the spreading center (see diagram on opposite page). As a result, that newly attached portion of

(Opposite) (a) Jurassic-Cretaceous (compressional phase): The Pacific and Farallon Plates grow and move away from each other as new igneous (volcanic) bedrock is added to them at the East Pacific Rise (a spreading center). The Farallon Plate subducts beneath the North American Plate. The subduction generates magmatic activity and forces uplift on the crust of the North American Plate, both of which contribute to mountain building. The Pacific Plate is also moving, together with the Farallon Plate, toward North America (large gray arrow). (b) About 45 million years ago: The East Pacific spreading center meets the North American Plate and is "dragged" beneath it by the pull of the submerging Farallon Plate. (c) Beginning about 35 million years ago (extensional phase): The Eastern Pacific spreading center, still active, begins to create a rift on the margin of the North American Plate, the western portion of which becomes attached to the westward-moving Pacific Plate. As western North America is pulled to the west with the Pacific Plate, it is stretched and thinned, creating the widespread Basin and Range topography we see today (that includes the Sky Islands). It eventually opens a trough, shallow at first, but then deep enough that it fills with seawater to create the Gulf of California (about 6.5 mya). (d) Today, the Baja California Peninsula and the southern half of California are still moving northwestward, attached to the Pacific Plate.


a
East Pacific Spreading Center
Mountains uplift
Volcanos erupt
Pacific Ocean
NORTH AMERICAN PLATE
PACIFIC PLATE
FARALLON PLATE
Molten lava
Magma chamber
b
Pacific Ocean
NORTH AMERICAN PLATE
PACIFIC PLATE
FARALLON PLATE
East Pacific Spreading Center
c
Pacific Ocean
NORTH AMERICAN PLATE
PACIFIC PLATE
FARALLON PLATE
d
Gulf of California
Basin and Range Province
Pacific Ocean
NORTH AMERICAN PLATE
PACIFIC PLATE
Extension
FARALLON PLATE



This map shows the Basin and Range Province, the highlands (e.g., Colorado Plateau, Sierra Madre Occidental, and Sierra Nevada) that confine the Sonoran Desert, and the largest canyon systems of the region.

North America began moving northwest, and as it did so, it pulled on the crust, stretching it. In the Basin and Range region it thinned in some places to only half its original thickness.

As the crust stretched, it began to crack, like the surface of a cooling pumpkin pie. As it cracked, great blocks of earth dropped downward in vertical block faulting. These became valleys, while the remaining high land persisted as mountain ranges. So widespread was this extensional block faulting that it created about 500 isolated mountain ranges that we see today, extending from southern Oregon and Idaho to central Mexico, including most of the Sonoran Desert and southeastern Arizona. This massive region, with its distinctive basin

Pupfish

A few isolated springs in the Sonoran Desert contain varieties of small cyprinodontid fish known as pupfish (*Cyprinodon* spp.), including the desert pupfish, *C. macularius*, and Quitobaquito (or Sonoyta) pupfish, *C. eremus*, both of which are federally listed as endangered species. Some of these unlikely little desert survivors can tolerate saline water nearly twice as salty as the ocean and water temperatures up to 110°F (43°C) or more. The dispersal of pupfish species across much of Basin and Range country, even into totally isolated valleys, probably occurred during the wetter Pleistocene, when the Colorado River system flowed more vigorously and allowed them to explore all the backwaters of this aquatic kingdom. In drier times, their habitats shrunk back to only the perennial springs they inhabit today. At least two varieties of pupfish have gone extinct—the Santa Cruz or Monkey Spring pupfish (*C. arcuatus*) in Arizona was eliminated by introduced largemouth bass predation in 1969, and the Tecopa pupfish (*C. nevadensis calidae*) near Death Valley vanished about 1970 due to habitat alteration and nonnative species. Across the region, land development and the introduction of exotic fish like mosquitofish, largemouth bass, and tilapia, as well as changes in climate, have devastated pupfish populations. Today, desert pupfish are no longer present naturally in Arizona and are restricted to a few parts of their former range in California and northwestern Sonora, Mexico, and Quitobaquito pupfish persist only at a single site in Arizona (Quitobaquito Springs in Organ Pipe Cactus National Monument) and in the nearly dry Sonoyta River just south of the U.S.-Mexico border. The pupfish survival story, like so many others, continues to unfold as the Sonoran Desert evolves.

and range topography, is known as the Basin and Range Province.

This extension phase persisted from about 35 million years ago until at least 6 million years ago, when the Baja California Peninsula pulled right off of Mexico, creating the Sea of Cortez (Gulf of California). Most of the modern-day movement between the Pacific and North American plates is called *transform* motion, where one plate slides by another along a fault that is parallel to plate movement direction. Once the peninsula had separated from mainland Mexico, transform motion occurred right up the middle of the Sea of Cortez, under the delta of the Colorado River and up through Southern California (where we know it as the San Andreas Fault), all the way to Point Reyes (north of San Francisco), where the spreading center and transform faulting moved offshore and back into the Pacific Ocean. Baja and Southern California, which lie west of this great plate boundary, continue to be pushed to the northwest at a rate of about 2 inches (5 cm) per year. Frequent earthquakes in California and northwestern Mexico remind us that the land is still on the move.

In a few of the Basin and Range mountains, the granitic and gneissic rocks deep in the Earth's crust were displaced upward beneath gently dipping faults, eventually to be exposed on the surface. Movement on these gently dipping faults is called *detachment faulting*, and it is quite distinct from the more typical block faulting. In the Santa Catalina Mountains, northeast of Tucson, the upper layer was gradually pulled westward for miles across the detachment fault; there is compelling evidence that this is how the Tucson Mountains moved to where they are today, west of Tucson; the Tucson Mountains were once a volcano on the western side of the Santa Catalinas! In fact, the phenomenon of detachment faulting was first discovered in the Santa Catalinas, by scientists from the University of Arizona.

By about 6 million years ago, it seems that the extension had stopped, the thinned crust had cooled, and the Basin and Range mountains and valleys had stabilized. Since that time, the chief geologic activity has been the erosion of rocks off mountains and into adjacent valleys. Most Basin and Range valleys are filled with 5000 feet (1525 m) or more of gravel, sand, and clay beds—the geologic containers for our only major regional aquifers. Basin and Range country is unique; no other such extensive region of similar origin is known on the planet. All four of North America's great deserts lie within the Basin and Range geological province. Plates 4, 6, 9, and 13 show the end result of Basin and Range formation and the long period of subsequent erosion.

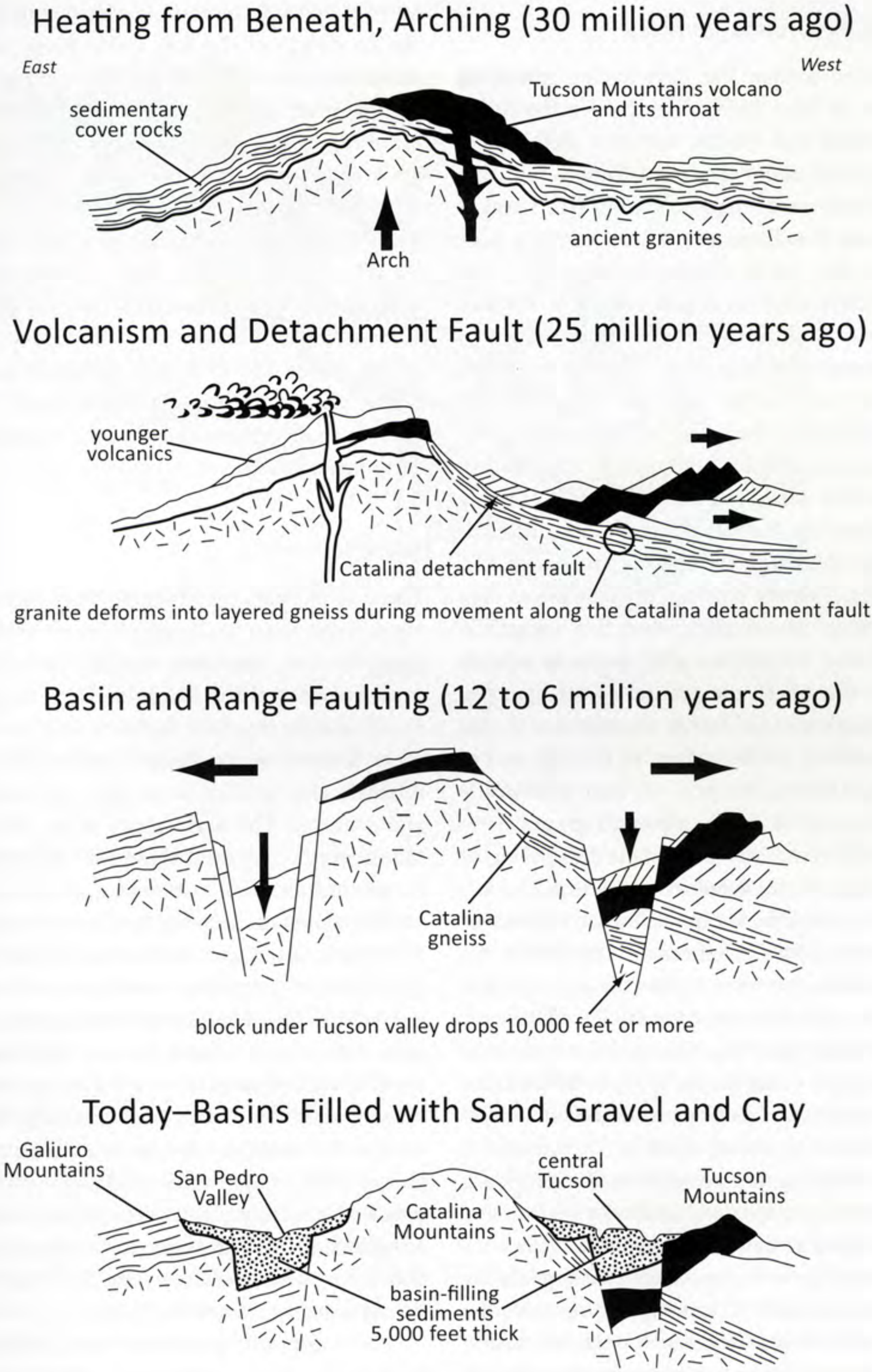
The Sonoran Desert Landscape Today

The Sonoran Desert lies in the heart of the Basin and Range Province. Thus, this curious country consists of broad, low-elevation valleys rimmed by long, thin, parallel mountain ranges (see map on page 76). Intermittent streams and dry washes in each valley connect either to a major through-flowing river, such as the Gila or Salt Rivers (see plate 9), or else drain into a valley's internal low spot where a salt-encrusted playa (or dry lake) forms, such as Willcox Playa in Arizona and Playas Lake (east of the Pyramid and Animas Mountains) in New Mexico.

On its northern edge, the Sonoran Desert is bounded by a mile-high escarpment called the Mogollon Rim, the distinctive southern edge of the Colorado Plateau. The Colorado Plateau extends northeast across Utah, New Mexico, and western Colorado. It consists of a massive "pancake" pile of sedimentary rocks of diverse age (from 7 million to 1.7 billion years old), exposed over a wide area, but most famously in the walls of Arizona's Grand Canyon National Park. The eastern edge of the Sonoran Desert consists of a honeycomb series of mountains and valleys of increasing elevation. In fact, the elevations of valley bottoms across the Sonoran Desert rise from sea level near Yuma on the west to 5000 feet (1525 m) in southeast Arizona, where deserts are replaced by grasslands. The southern extent of the Sonoran Desert is set by climate, as winter freezes disappear and hot, moist summers transition the landscape from desert to thornscrub and tropical deciduous forest in central and southern Sonora. But other geological features are also at work in our region.

The Sonoran Desert lies west of the great North American Cordillera. To the east of the cordillera lies the Chihuahuan Desert. But these two huge and biologically diverse deserts do meet and mingle—in one place. Remember the Cordilleran Gap? Here, in southeastern Arizona/northeastern Sonora, the vegetative communities (and their associated faunas) of these two deserts stretch through this gap to form interdigitating patches of Sonoran desertscrub and grassland, and Chihuahuan desertscrub and grassland. Take a drive through Sulfur Springs Valley and you'll see these patchworks of subtropical Sonoran Desert and warm-temperate Chihuahuan Desert plant communities. So the gap provides what is known as a biogeographical corridor, for plants and animals from very different regions to extend their ranges. But the Cordilleran Gap is also a biogeographical barrier, for it breaks the continuity of the cordillera itself, thus inhibiting the movement of montane plants and animals.

Recall that the Sonoran Desert sits in the middle of the massive Basin and Range Province, and many of those Basin and Range mountains are scattered through the Cordilleran Gap. The higher of these ranges—ones capable of harboring montane biological communities—are Sky Islands that act as stepping stones for the dispersal of plants and animals north and south from the Rockies and Sierra Madre. The large range of elevations and habitats, and the mixing of subtropical and temperate deserts, as well as montane biota from the north and the south, give the Sky Island Region an extraordinary biological diversity. In fact, the U.S. portion of this region is probably the most biologically diverse area in all of the United States and Canada. And it's one of the reasons southeastern Arizona is so popular with birders (there are over 500 species of birds here, more than half the species known from all of the United States and Canada).



Geologic cross sections through the Tucson area illustrating the recent geological history of the Sonoran Desert

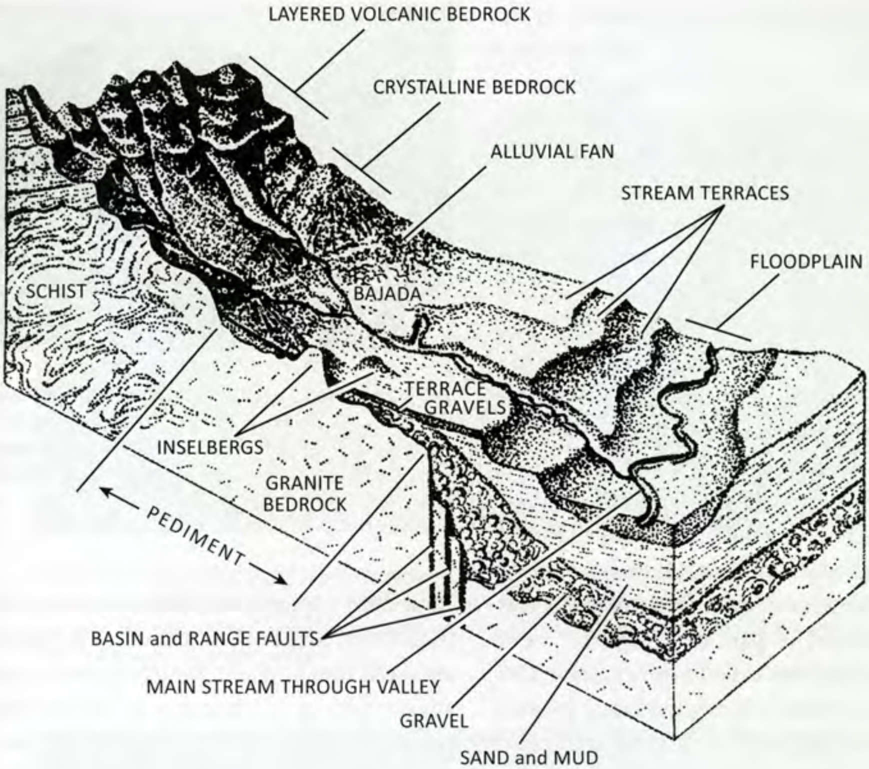
When the Ground Trembles

As noted earlier, the East Pacific spreading center, or East Pacific Rise (where the North American and Pacific tectonic plates meet today) runs under the Sea of Cortez and north from there more than 700 miles (1120 km) to just past San Francisco, where it angles back out to the Pacific Ocean seafloor. From the Salton Sea northward it is known as the San Andreas Fault. However, this huge fault area comprises not a single fault line, but a complex mix of "sister faults" (adjacent parallel faults) and transform faults (short horizontal faults that are connected at both ends to other faults). In fact, the whole complicated mess is properly called the San Andreas–Gulf of California Fault System. Although the tectonic plates are continually, if slowly, moving, in some places they get "stuck" temporarily; when they eventually break free, the sudden shift produces seismic waves that shake the ground as earthquakes. Earthquakes in California, associated with this fault system, are legendary. In general, east of Yuma, Arizona, the land has been seismically quiet in recent times, although ground ruptures in Green Valley and Gila Bend suggest prehistoric earthquakes in those areas. The last major earthquake felt in the Tucson region was on May 3, 1887. That afternoon the Earth's surface ruptured some 20 miles (32 km) south of Douglas, Arizona, near the village of Bavispe, Sonora (see plate 30). The quake is estimated to have had a magnitude of 7.4 on the Richter scale. It was responsible for 51 deaths in Mexico, while cracking plaster walls in Tucson and El Paso, knocking over an adobe wall at the Spanish cemetery at Mission San Xavier del Bac near Tucson, and stopping large pendulum clocks in Phoenix. Tucson residents reported large clouds of dust and forest fire smoke rising above the crest of the Santa Catalina Mountains and first thought it to be an erupting volcano. Apparently, the fires were ignited by falling boulders crashing together and causing sparks on the dry hillsides. Tohono O'odham residents at the village of Pan Tak, below Kitt Peak, reported a massive rockfall. Geysers of water shot up from the floodplain of the San Pedro River, while other streams and springs throughout the region either dried up or initiated flow. Many more recent but relatively minor earthquakes are known along that zone south of Douglas. Most recently, in 2010, a 7.2-magnitude earthquake shook the Mexicali-Calexico area, a shock felt all the way to the Pacific Coast as far north as Santa Barbara; although it was not felt in Tucson, it was recorded on instruments. This quake, called the El Mayor–Cucapah Earthquake, was on the Laguna Salada Fault. This same fault was responsible for a 7.2-magnitude earthquake in 1892.

Young Volcanism

There have been two distinct types of volcanism in the Sonoran Desert in recent geologic time. The first, associated with the intense volcanic episodes of the Laramide Orogeny, produced mainly rhyolites (light-colored volcanic rocks formed on the Earth's surface that are relatively rich in silica, aluminum, potassium, and sodium). The main mass of the Tucson Mountains is composed of red and yellow rhyolite produced during a volcanic episode on the western slopes of the Santa Catalina Mountains 70 million years ago (see illustration on page 79). Rhyolite volcanoes tend to explode violently, like Mount St. Helens or Krakatoa. The other type of volcanism is seen in the younger volcanic rocks formed during Basin and Range orogeny (over the last 10 million years); these are mostly basalts (dark-colored volcanic rock, rich in iron, magnesium, and calcium) that rose to the surface along deep cracks. Basaltic eruptions are nonexplosive; they produce lavas with a consistency of 80-weight motor oil that spread quickly across valley floors.

There are three prominent basalt fields in the Sonoran Desert, all formed within the past 4 million years. One of these, the Pinacate field just north of Puerto Peñasco, Sonora, has rightfully become an international showcase of natural history, recognized as a UNESCO Biosphere



Typical Sonoran Desert landforms

Reserve and World Heritage Site. The field contains a central 4000-foot-tall (1220-m) stratified volcano composed of multiple lava flows and ash layers, surrounded by approximately 400 outlying basalt cinder cones and flows (see plate 14) and 10 unusual steam-blast explosion craters, called *maar craters,* some with diameters in excess of a mile (1.6 km). These unusual craters owe their explosive origin to an encounter of the rising magma with underground water-saturated sediments, which adds the force of steam blasts to the normal volcanic fountain. Other significant basalt fields are the Sentinel field west of Gila Bend and the San Carlos field east of Globe. There are also two small fields in north-central Sonora.

Sonoran Desert Landforms Today

The Sonoran Desert contains a characteristic series of landforms, shown in the illustration above. Sparse regional rainfalls tend to lack the force to move sediments very far from the mountains. However, rare heavy rains produce torrents of mud, rocks, and vegetation that cascade rapidly down steep, narrow canyons in the mountains. These rocky mud masses spread out in front of the mountains in gently sloping cones called *alluvial fans* (see photo on page 82). Vigorous mudflows can move boulders the size of small ships. When neighboring alluvial fans coalesce along a mountain front, the resulting landform is a broad, sloping plain around the base of the range, called a *bajada* (bah-HAH-dah). Another significant feature of desert mountain-range geology is the *pediment*—a buried shoulder of bedrock that extends from the edge of the mountain some miles toward the valley center, where it meets a buried fault. Beyond the fault lies much thicker valley alluvium (gravel, sand, silt, and clay). Pediments form as the mountain front is worn back with time, the shoulder buried with layers of gravel as the valley fills with alluvium. Although these pediments are not visible to us, they have been important for human development, as they serve to confine the main valley aquifer (see illustration on page 81). Isolated small hills near mountains, called *inselbergs*, are exposed bedrock masses that have not worn away; they are a sure sign of the pediment's presence.

Today, larger valleys in the Sonoran Desert contain one or more main stream channels that are normally dry. The flatland adjacent to these stream channels is subject to flooding during larger storms—thus, the term *floodplain*. But since the 1890s, river floods have tended to incise and widen the main channels, so that the floodwaters do not flow out onto the floodplains, except locally. This recent channel enlargement is part of a regional trend throughout the West called *arroyo cutting*. One likely cause of this is increased cattle grazing following development of regional railroads in the 1880s. (Healthy grasses facilitate rainwater retention in the soil, recharging local aquifers, while overgrazed lands encourage fast runoff into streams and rivers, resulting in increased velocity and forces capable of incising river banks). Other likely causes include devegetation of hillsides by the mining industry for mine timbers and smelters, and climate shifts. In the late twentieth century some local communities attempted to stabilize channel embankments with soil cementation, but that approach resulted in heavier flood flows and bank-caving downstream. This occurs because the cement-lined channel walls prevent infiltration and force more water down the channel. In the twenty-first century that approach has been largely abandoned in the larger urban centers.

Alluvial fan. Boulder debris in front of the Gila Mountains near Yuma. Large rocks like these are transported in massive debris flows down steep canyons; they spread out along the mountain front during times of rare, intense rains.

In the mountains, a different kind of erosion has fostered delightfully fantastic scenes. Over eons, balanced boulders have formed by erosion of certain rock types, such as granite and thickly layered sandstone or volcanic ash. These rocks weather along cracks or joints and tend to form spires or irregular columns. Rounding happens, as corners weather faster than sides, just as the cube of ice in your iced tea melts into a sphere. Boulders are eventually shaken free by earthquakes or uneven weathering and fall over. Balanced boulders can be seen along the Gates Pass road in the Tucson Mountains, in Texas Canyon along Interstate 10 east of Benson, on Camelback Mountain (Echo Canyon) in Phoenix, and in many of the Sky Islands (notably the Santa Catalinas and Chiricahuas). These same kinds of rocks, when more fracture-free, can weather into large, spectacular domes that develop concentric rounded joints just like a layered onion, from which segments of layers separate, exposing a cone-shaped core. Spectacular conical granite domes with "onion-peel" structures may be seen along the high ridges on the west side of the Santa Catalina Mountains above Catalina State Park, and in the Tortolita Mountains northwest of Tucson. *Hoodoos* (an informal term) are a special category of balanced boulders—tall, thin spires of many rock types that form in areas where bedrock is broken by multiple sets of vertical fractures and where canyon cutting is intense. Hoodoos are obvious along the Mount Lemmon Highway at Windy Point and Geology Vista, and in Chiricahua National Monument.

Cliffs of volcanic tuffs exposed along the western front of the Kofa Mountains near Oak Canyon in western Arizona. The volcanic eruption that created these mountains was but one of hundreds that occurred throughout the Southwest and northwestern Mexico between 40 and 20 million years ago. (Photo Kresanphotography.com)

A star dune field along an isolated set of hills northwest of Puerto Peñasco, Sonora, Mexico. Sand for this dune field is blown in by wind from the coast of the Sea of Cortez. (Photo Kresanphotography.com)

Mountains composed of volcanic layers have weathered into rugged tablelands cut by sharp canyons, such as in the Ajo, Tumacacori, and Kofa Mountains (see photo on page 83). The sharp eye may spot a sizable vertical cylinder of resistant rock weathering away from a volcanic cliff; often, this is a volcanic "neck" or "plug" formed in the feeder vent for a volcanic flow. There are good examples of volcanic necks in the Superstition, Tucson, and Ajo Mountains.

Sand dune fields are common in the Sonoran Desert. Dune fields occupy downwind portions of valleys where wind-dispersed sand has accumulated. The Gran Desierto de Altar (including the Algodones Dunes east of El Centro and the Mohawk Valley field east of Yuma) is the largest active dune field in North America. Its sands were mostly derived from the Colorado River Delta, blown there by prevailing winds over the past 25,000 years or so (see plate 29). Thus, this great sea of sand is a remnant of the Grand Canyon, long ago eroded by the Colorado River and carried down to the delta, from whence it was carried east by winds to end its long journey as sand dunes in Mexico. The Gran Desierto contains examples of several dune types, including beautiful star dunes, which each have several radiating sharply crested sand ridges coming off a high point (photo on page 83). The vast Cactus Plain dune field near Parker derives its sand from the old shoreline sands of the Colorado River. Minor dune fields are found throughout the region, their sands derived from local river floodplains. There are many less obvious, vegetated dune fields, such as those east of Green Valley and along the Gila River north of Florence.

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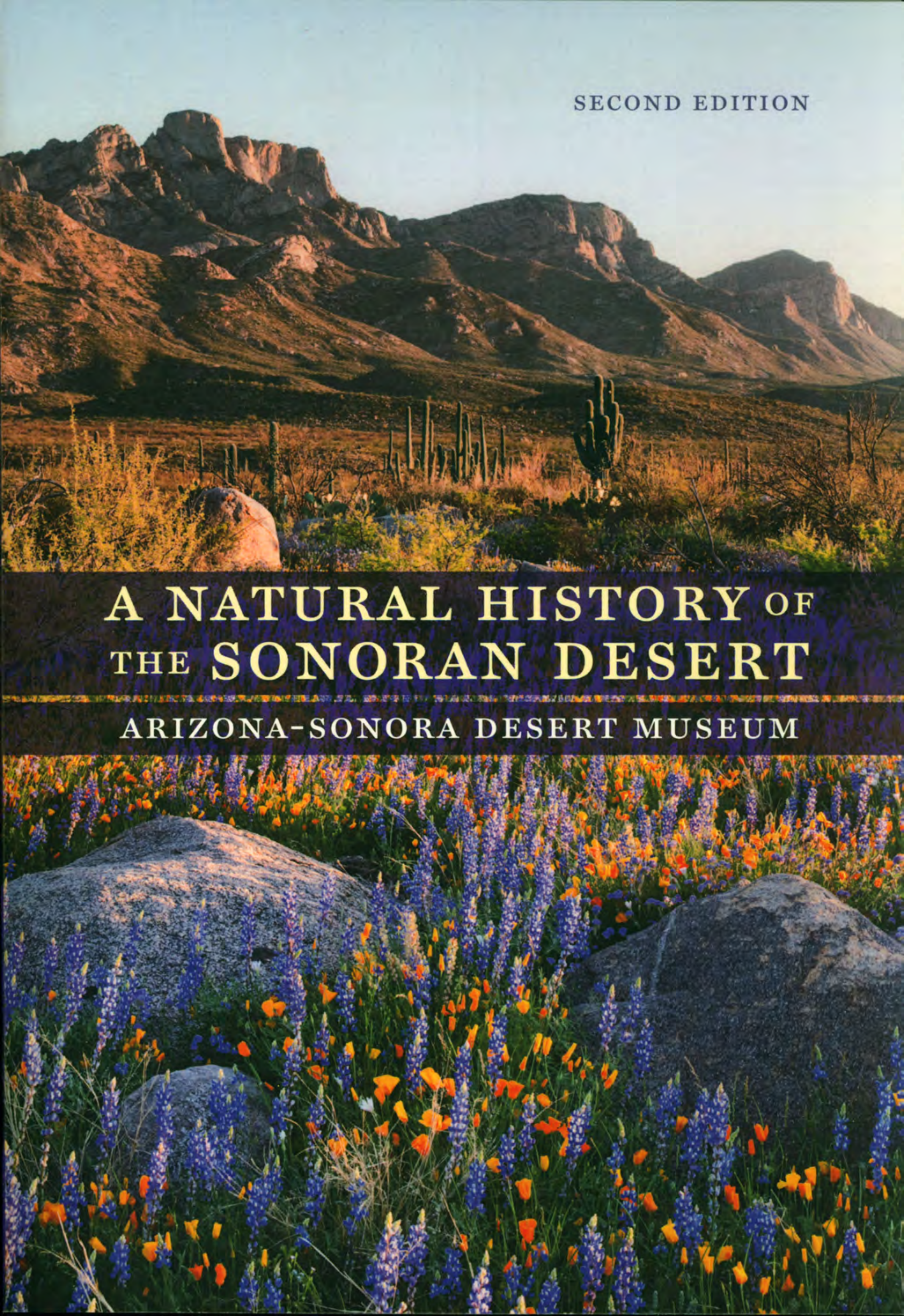
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