**A BRIEF GEOLOGY OF NORTHWESTERN MEXICO**

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NOTE: This document is periodically updated as new information becomes available (see *date stamp* above).

Sections



## Geological Origin of the Baja California Peninsula and Gulf of California

Although the Gulf of California (aka, "the Gulf," the Sea of Cortez) is a young sea—less than 6 million years old (mya)—the present-day topography of its basin and the Baja California Peninsula evolved through a series of grand geological events that began many millions of years ago, long before the peninsula itself formed.

Between about 140 mya and 80 mya (Cretaceous Period), the Farallon Plate, an eastward-moving seafloor lithospheric plate, was being dragged beneath (subducted) the western edge of the North American Plate. The Farallon Plate was spreading eastward from an active seafloor spreading center called the East Pacific Rise (Endnote 1). To the west of the East Pacific Rise, the gigantic Pacific Plate was moving westward relative to the North American Plate, powered by the same spreading center and tectonic forces. But plate dynamics were (and still are) complicated, and the East Pacific Rise was itself also drifting slowly eastward, following along "behind" the Farallon Plate, and the North American Plate was simultaneously moving slowly westward as the Mid-Atlantic Ridge continued to open (as it still does today).

At first, the Farallon Plate's angle of subduction was steep, about 45 degrees, which is typical of submerging plates. Some evidence suggests that, for a time, the subduction angle of the Farallon changed and the plate began moving under North America at a shallow angle. The plate eventually pushed nearly 1000 miles (1500 km) under the North American Plate before switching back to a steep angle of subduction. It is thought that this shallow subduction caused a drag on the overlying crust of the North American Plate, pulling on it to squeeze and compress it, crumpling its surface into mountains like a wrinkled rug pushed from one edge.

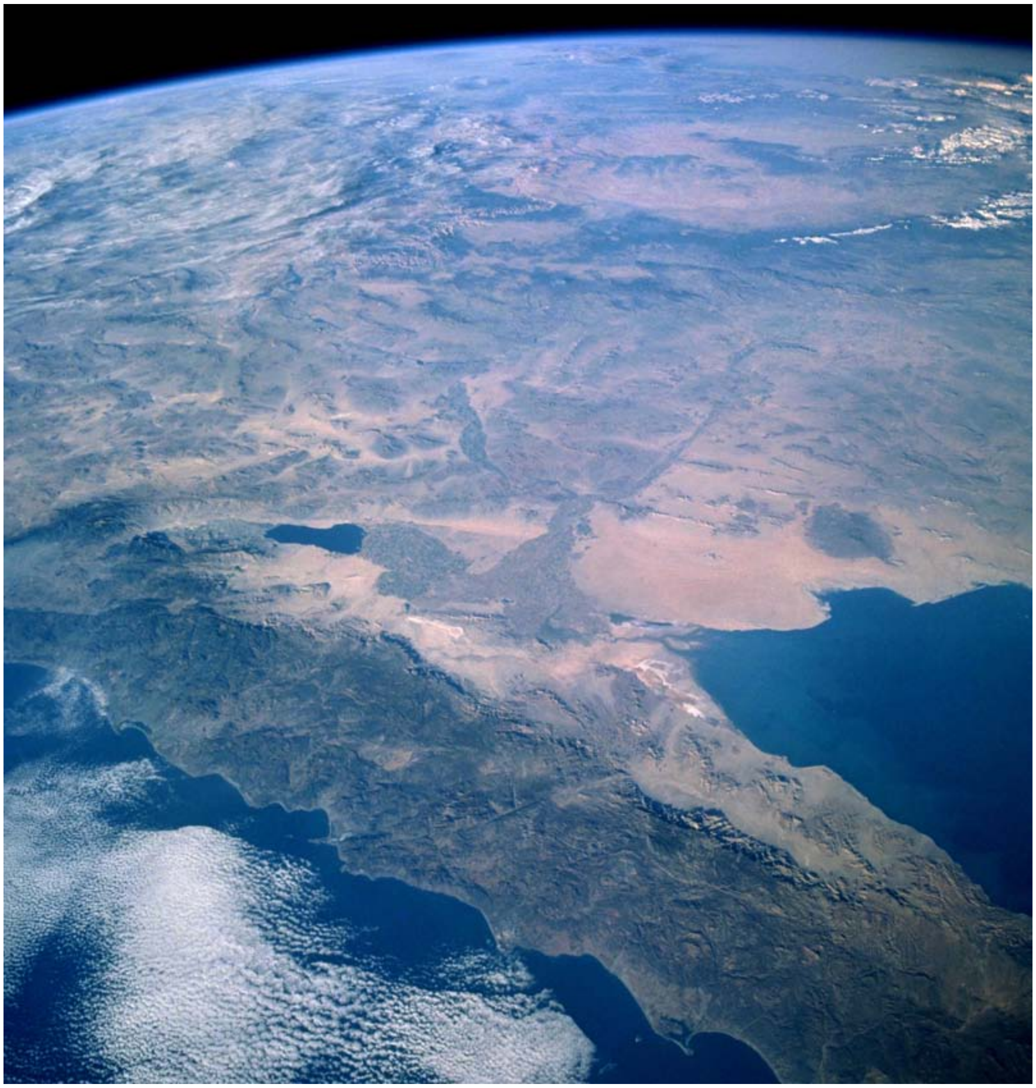
Whatever the cause, there was a period of mountain building associated with the Farallon subduction that took place in a series of pulses and intervening quiescent phases. This great mountain-building event, known as the Laramide Orogeny, extended from southern Canada to northern Mexico, and as far east as the Black Hills of South Dakota, and it included the Laramie Mountains of Wyoming (for which it was originally named).

| ERA | PERIOD | | EPOCH | TIME (beginning ) |
|---|---|---|---|---|
| Cenozoic | Quaternary | | Holocene | 10,000 ybp |
| | | | Pleistocene | 2.6 mya |
| | Tertiary | Neogene | Pliocene | 5.3 mya |
| | | | Miocene | 23 mya |
| | | Paleogene | Oligocene | 33.9 mya |
| | | | Eocene | 55.8 mya |
| | | | Paleocene | 65.5 mya |
| Mesozoic | Cretaceous | | | 145.5 mya |
| | Jurassic | | | 201.6 mya |
| | Triassic | | | 251 mya |
| Paleozoic | Permian | | | 299 mya |
| | Carboniferous | | Pennsylvanian | 318 mya |
| | | | Mississippian | 359 mya |
| | Devonian | | | 416 mya |
| | Silurian | | | 444 mya |
| | Ordovician | | | 488 mya |
| | Cambrian | | | 542mya |
| Precambrian | | | | 4500 mya |

Geologic Time Table (Designed by R. Brusca and L. Brewer)

During this long period of subduction, the oceanic rocks of the Farallon Plate were carried deep enough to melt and create magma. Some of this magma crystallized below the surface to form granitic batholiths, including those that are now found in the Sierra Nevada and Peninsular Ranges in California and along the length of the Baja California Peninsula. Much of it, however, erupted at the surface as andesitic volcanoes, probably looking very much like present-day Mt. St. Helens in the Cascade Range. The Laramide Orogeny also produced many of the mountains seen today in western North America, including the Rocky Mountains and much of the Sierra Madre Occidental of Mexico, the two great ranges that together comprise North America's Western Cordillera. (Endnote 2).

In addition to the igneous rocks that were formed by subduction, the Farallon Plate and other small plates moving eastward in the Pacific Basin carried on their backs numerous volcanic oceanic islands and archipelagos, both submerged and emergent. When these high-standing oceanic islands and seamounts encountered the continental margin, they were scraped off as the plates slowly dived beneath the North and South American continents. These accreted allochthonous, or "exotic" terranes, whose origins were long a geological mystery, stretch from Alaska to South America, and they not only augmented and built-out the continental landmasses, they also created many of the coastal mountain sections that we can recognize today. In fact, nearly all of North America west of the Basin-and-Range Province consists of a heterogenous patchwork of these allochthonous terranes, accreted onto the edge of the North American Craton (what is left of the ancient continent of Laurentia) from the Paleozoic to as recently as Late Miocene. Although no



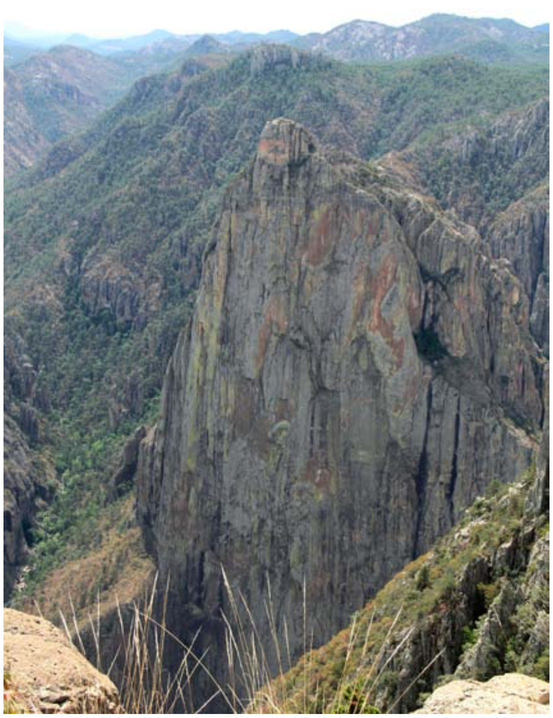
NASA image of the Colorado Plateau, Mogollon Rim, Lower Colorado River Basin, and the Upper Gulf of California

allochthonous terranes have been positively identified in Arizona or Sonora, most of the Baja California Peninsula and western Mexico probably consist of these ancient relocated land masses.

The great Central Valley of California is itself an ancient forearc basin, preserved between the Pacific Coast mountain ranges and the Sierra Nevada. Southeastern California and adjacent Arizona/ northwestern Mexico lie within the fragmented transform boundary between the Pacific and North American Plates.

During the Tertiary period, Baja California was attached to western North America, and the Farallon Plate was being subducted eastward beneath the Baja-Mexico margin (the North American Plate). Volcanism related to this subduction occurred in the Sierra Madre Occidental of mainland Mexico from 100-45 mya and 34-23 mya, and in eastern “Baja California” and westernmost Sonora from 24 to 10 or 8 mya.

As the Farallon Plate steadily subducted and disappeared beneath North America, the final phase of subduction, between Sonora and what is now the Baja California Peninsula, resulted in a continental volcanic arc forming ~24-15 mya. The rocks generated from this volcanic arc now constitute the uplifted mountains of the easternmost Baja California Peninsula, exposed as thick andesite flows in the Sierra La Giganta (west of the town of Loreto) as well as mountain ranges in southwestern Sonora.



Barrancas del Cobre (Copper Canyon), Sierra Madre Occidental (Photo by Jim Welden)

Subduction ended when the leading midregion of the Farallon Plate finally disappeared beneath North America, and the East Pacific Rise itself came to intersect the North American Plate. This happened ~25-30 mya in central California, and ~12-15 mya in northern Mexico. Because the Farallon Plate was irregular in shape, its northern and southern tips lagged behind and fragmented into microplates that continue to move slowly against and under the North American Plate. The northern remnants of the Farallon Plate are today called Juan de Fuca, Explorer, and Gorda Plates (in northern California, Canada, and Alaska). The southern fragments are known as the Cocos Plate (currently subducting under southern Mexico and Central America), and the Nazca Plate (currently subducting under South America).

As the East Pacific Rise subducted beneath western Mexico, the portion of North America’s crust west of the spreading center gradually became attached to the Pacific Plate. The attachment began around 12 mya, and was fully completed ~4 mya. The attachment of a small fragment of crust from one plate (in this case, the North American Plate) to another (in this case, the Pacific Plate) is not uncommon in geologic history. The now-enlarged Pacific Plate continued to be driven westward by the East Pacific Rise spreading center. By Mid- to Late Miocene, 14–7 mya, the entire mountainous margin of northwestern Mexico had become coupled to the northwestward-moving Pacific Plate and had begun to gradually pull away from the North American continent. Short segments of seafloor

A river in the Sierra La Giganta, west of Loreto, central Baja California Sur (Photo by R. Brusca)

spreading, associated with long sections of transform faults (the present-day San Andreas-Gulf of California Fault System), stretched and thinned the continental crust. This initial rifting and crustal thinning took place in the Mid- and Late Miocene ~13-6 mya), creating an area of crustal subsidence in northwestern Mexico consisting of a northwest/southeast-trending extensional trough in the spreading region. This trough is known to geologists as the Proto-Gulf Extension, Proto-Gulf Rift, or simply the Proto-Gulf. The entire affected area has been called the Gulf Extensional Province, generally considered to extend from the eastern shores of the Baja California Peninsula to the base of the pediment of the Sierra Madre Occidental. The Proto-Gulf concept was originally used by Moore and Buffington (1968) to explain an area of anomalously old oceanic crust adjacent to the margin of the Gulf of California. However, it was probably Karig and Jenski (1972) who first codified the term "Proto-Gulf" in reference to the extension, in the sense of analogy to other "volcano-tectonic rift zones associated with an active trench-arc system." Subsequently, the term "Proto-Gulf" has frequently been inappropriately used as a synonym for the presence of early, pre-Gulf of California basins and marine incursions into the region. However, the term should properly be restricted to reference the extensional event that created the Gulf Extensional Province ~13 to ~6 mya. The modern Gulf of California, on the other hand, is a product of seafloor spreading and transform faulting since ~6.0 to 5.5 mya.

The amount and direction of extension in the Gulf Extensional Province has not been well understood and was long a major missing piece in our understanding of northwest Mexico. However, recent work (Henry & Aranda-Gomez 2000) suggests that this episode of extension affected the entire southern Basin and Range Province, from southern Arizona and New Mexico to the Trans-Mexican Volcanic Belt, and even across the northern and southern ends of the Sierra Madre Occidental. Batholiths generally resist extension, and the Henry & Aranda-Gomez model holds that the stable batholiths of the Sierra Madre and Peninsular Range of Baja California constrained the extensional event to the Gulf region by resisting extension, thus resulting in two great branches of the Basin-and-Range Province (east and west of the Sierra Madre Occidental). The eastern branch occupies most of north-central Mexico east of the Sierra Madre Occidental and has undergone several separate episodes of extension, beginning in the late Oligocene or early Miocene. The western branch borders the Gulf of California west of the Sierra Madre and is what has been called the Gulf Extensional Province. Importantly, the two branches are contiguous across both Sonora to the north and Nayarit to the south, such that the Sierra Madre Occidental can be viewed as an unextended batholithic island surrounded by extended terrain.

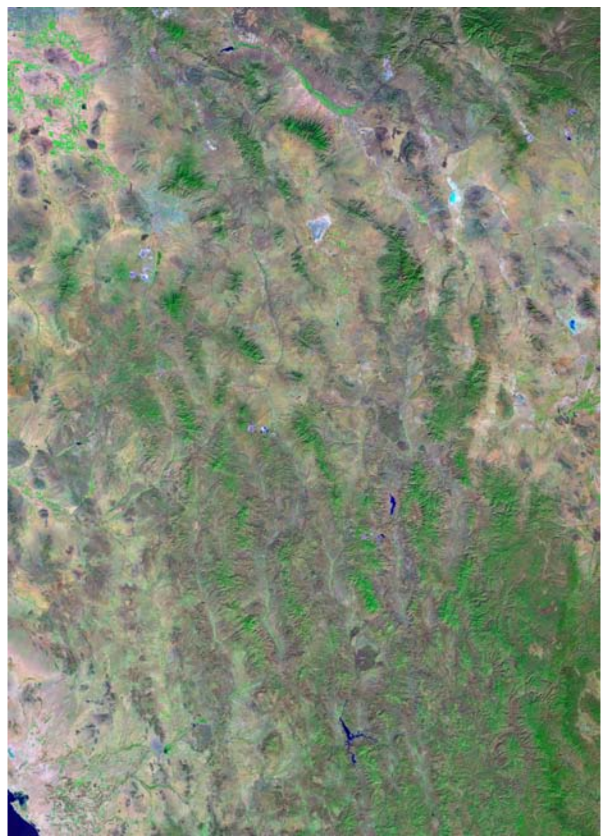
Thus, the Gulf Extensional event (and the Proto-Gulf) are part of the same pulses of crustal extension that created North America's Basin-and-Range Geological Province. All of this was driven by the extension created as the East Pacific Rise submerged beneath the western edge of the North American Plate, starting first in Mexico then progressing northward to northern California, to capture a slice of western North America. There is some evidence that rapid, large-magnitude extension pulses were associated with extensive magmatic activity, suggesting that the input of heat from the mantle may have enhanced crustal extensional collapse in some regions.

The thinning of the continental crust throughout this huge region resulted in the creation of some 400 mountain blocks of exposed, ancient rocks known as the Basin-and-Range Geological Province, which extends as far north as Oregon, and southward into west-central Mexico. The basins are down-fallen blocks of crust; the ranges are blocks that were uplifted relative to (and bordering) the fallen blocks. Due to thinning, the continental crust of the Basin-and-Range Province is about half the thickness of the continental crust elsewhere in North America. This widespread extension also resulted in localized eruptions of basalt lava. In southwestern Sonora, in the Sierra Libre and Sierra Bacatete, these basalts erupted between 13 and 8 mya. Similar ages have been obtained from basalts of the Baja California Peninsula.

The precise timing, magnitude, and distribution of crustal extension in the Basin-and-Range Provice is not well understood. The total amount of extension is probably 50-100% (i.e., up to a doubling of width of the crust in the region), but this occurred unevenly throughout the Basin-and-Range province, and less extension seems to have occurred westward. Extension was also highly episodic, with the timing varying from place to place (although three major episodes have been proposed). In some areas, extension was on-going in the Eocene, whereas in other places it did not begin until the Mid-Miocene. Northern Mexico, including all or most of the states of Sonora, Chihuahua, Durango, Sinaloa, and Nayarit encompasses nearly half of the total Basin-and-Range extensional province, although the Sierra Madre Occidental shows almost no evidence of extension. Almost all of the extension in Sonora occurred between ~25 and 10 mya, although the age of the extension decreases from east to west.

As the crust of western North America continued to thin, the Proto-Gulf of California Extension grew, allowing for one or more temporary marine transgressions, or incursions of the Pacific Ocean onto mainland Mexico, between ~13 and ~6 million years ago. These large embayments, or seaways were probably similar to the ancient seaway in California that once filled that state's great Central Valley through the San Francisco gateway. As noted above, these marine incursions or embayments have sometimes been misleadingly referred to by using the geologic term, "Proto-Gulf"—but there is no physical evidence they had any connection to the modern Gulf of California so this usage is misleading. A few authors have interpreted the sedimentary and paleontological data of these Miocene embayments not as transient marine transgressions onto the continent, but as evidence for an actual Middle Miocene separation of the Baja Peninsula and opening of the Gulf; but geological data do not support that idea. The Gulf Extensional Event (described above) created Proto-Gulf rifting, but this preceded seafloor spreading and opening of the present-day Gulf of California.

The hypothesis of a Miocene northern Gulf is also contradicted by the presence in numerous localities of non-marine rocks that separate the early Gulf's sedimentary layers from the older sedimentary rocks of earlier Miocene marine embayments. For example, the Colorado River first met the Yuma area ~4 mya, as evinced by the appearance of coarse river sediments on top of the fine-grained sedimentary Bouse Formation. (Endnote 3)



The Sky Island Region of the Basin-and-Range Geological Province, seen from space (NASA images compiled by John Dohrenwend). Willcox Playa, in the no-outlet Sulfur Springs Valley, is the largest water body in the image (light blue, in upper center).

The Bouse Formation is a patchy fossiliferous mix of lacustrine sediments buried beneath the more recent Colorado

River gravels. The Bouse Formation sits above older Miocene, marine embayment sediments deposited before the modern Gulf of California had formed. The mix of lakebed sediments with scattered marine fossils confused interpretation of the Bouse Formation for many years, but recent evidence (e.g., Roskowski et al. 2010) suggests the formation represents a series of Colorado River lake basins, some of which became salinized enough to support a few species of clams and barnacles that were introduced from the Gulf of California or the Pacific Ocean (presumably on the feet or feathers of shore birds). The Roskowski et al. model argues strongly against marine influence anywhere in the Bouse depositional system, instead hypothesizing an interconnecting chain of lakes fed by the Colorado River. As river water arrived in each basin, it began precipitating the Bouse Formation as it filled. Once each basin reached capacity, water spilled over to create the next (lower) basin until, eventually, the river system connected to the Gulf of California 5-6 mya. Only one marine fish fossil has been described from the Bouse Formation, *Colpichthys regis* (the "false grunion"), an Upper Gulf of California endemic species.

In the Altar Basin, three major sedimentary sequences have been identified. The lower sequence records a Late Miocene ocean incursion of open-water marine conditions prior to the arrival of sediments from the Colorado River. The next sequence is early Pliocene (5.3-4.2 mya) and records Colorado River deltaic sediments. The uppermost sequence (late Pliocene-Pleistocene), which today outcrops near the small fishing village of El Golfo de Santa Clara (in northwesternmost Sonora), records fluvial and sub-aerial deposits with strong Colorado River input.

By 6 mya, extension within the plate boundary region had rotated the rocks oblique to the plate margin and rifting of the Baja Peninsula away from the mainland had begun—moving obliquely from south-to-north. As the Baja Peninsula pulled away from what is now mainland Mexico, ocean waters began to flood the newly formed low-lying basin and the Gulf of California gradually took form. Thus, while formerly part of the North American Plate, today the Baja Peninsula and most of southern California lie west of the spreading center and are part of the northwest-moving Pacific Plate. Since 6 mya, the peninsula has moved about 300 km westward from the mainland at the southern end of the Gulf, and it continues to swing open (like a hinged door) at a rate of about 4.6 cm/yr. (Endnote 4)

As the peninsula separated from the mainland, spreading-center seafloor basins in the Gulf might have opened more-or-less from south to north, from the María Magdalena Rise, to the Alarcón Basin, and on to the Pescador, Farallón and Guaymas Basins, and eventually to the far northern Wagner and Consag Basins. However, the sequence in which these basins developed active magmatic rifts was not necessarily in a perfect south-to-north progression. These basins are composed of genuine oceanic crust, constituting pull-apart basins bordered by alternating bands of magnetically oriented/polarized basalt. California's southern coast and southern Peninsular Range were uplifted coincident with Pliocene-Pleistocene movements of peninsular Baja California. The Gulf thus occupies a large rift valley between the Pacific and North American tectonic plates.

The Guaymas Basin is a narrow rift segment with high magma production and hydrothermal vents, and its lithospheric rupture probably occurred ~6 mya. The Alarcón segment is a wide rift that probably began 2-3 mya. The northernmost Wagner and Consag Basins have only recently been shown to be active spreading centers with hydrothermal activity, due to the difficulty of studying this region which is buried under ~7 km of sediments (here, the underlying crust is only ~15 km thick). These two shallow (~225 m) northernmost basins link the Delfín Basin to the south and the geothermally active Cerro Prieto Basin in the north (in the Mexicali Valley) along the Pacific-North American Plate boundary.

The rapid rate of opening of the Gulf has been attributed to three factors (Umhoefer 2011). First was the thinned and weakend crust, resulting from the Basin-and-Range Extensional Event (which thinned the crust by ~50% in much of the region, likely including the area west of the Sierra Madre Occidental). Second was the rapid rate of plate motion associated with the East Pacific Rise spreading center. Third was the oblique nature of the movement along the East Pacifc Rise spreading center, resulting in the establishment and dominance of strike-slip faulting that formed pull-apart basins. The strike-slip faulting is accommodted in the Gulf axis by linked transform faults and short spreading centers. Some workers consider today's Baja California Peninsula (and its associated segment of California) as a "microplate," even though it is "attached" to the Pacific Plate. Indeed, geological data indicate that the "Baja California Microplate" has been isolated as a rigid block within the Pacific-North America plate boundary zone since the Late Miocene. There is no geological evidence of Miocene crustal extension in the central part of the peninsula, and evidence suggests that the entire peninsula (at least from the latitude of Ensenada southward) remained essentially rigid throughout the Miocene and on into the Holocene. A proposed transpeninsular strike-slip fault in Baja Californai Sur (e.g., Crouch 1979) has not been conclusively validated.

Today the East Pacific Rise intersects the mouth of the Gulf, and it is expressed through the central axis of the Gulf as a series of transform faults known as the Gulf Rise spreading-center complex. Thus the Gulf of California comprises an oblique rift system with short spreading segments connected by long transform faults. The sum of these geotectonic activities created the "Gulf Extensional Province" (or "Gulf of California Geological Province") which includes the Salton Trough—a 125 mi (200 km)-long subsidence basin located in the complex transition zone between the San Andreas Fault system and the spreading center complex of the Gulf of California (Endnote 5). Today, the Colorado River delta largely fills the depression of the Salton Trough.

The Salton Trough is a graben (German for "grave"), a strip of land bounded on opposite sides by roughly parallel faults; in this case, bounded at its northern end by the San Jacinto and San Bernardino Mountains, on the east by the San Andreas Fault system, and on the west by the peninsular ranges (San Jacinto, Santa Rosa, Agua Tibia, Laguna Mountains in the United States; Sierra Juárez in Baja California).

The Gulf of California and Baja California Peninsula from space (NASA image). Strong easterly winds are blowing dust off the Plains of Sonora and Central Desert of Baja.

In the case of the Salton Trough, the graben has filled with more than 3.7 mi (6 km) of sediments eroded from adjacent mountain ranges as it subsided. Although not restricted to rift valleys, grabens are characteristic of them. Beneath the Salton Trough lies old oceanic crust.

The Salton Trough is essentially the "northernmost Gulf of California," the northern boundary being San Gorgonio Pass near Palm Springs (California). It is visible today as California's Coachella and Imperial Valleys, and Mexico's Mexicali and Yuma Valleys, Laguna Salada and Altar Basins, and the Colorado River Delta. The Salton Trough is the only part of the Gulf Extensional Province that is not covered by ocean water today, but it would be were it not for the barrier, or sill, of the 3325 sq mi (8612 sq km), 3.5 mi (5.6 km) deep Colorado River Delta sediments. The trough covers more than 2000 square miles (5180 sq km). About 16 mi (25 km) north of the California-Baja California border, abundant marine fossils of the Imperial Formation, in the Coyote Mountains, demonstrate that the Gulf reached farther north during the Early Pliocene.

Recent volcanism is evident in the Salton Trough in the form of rhyolite domes of Holocene origin at its southern end. Older, Pleistocene rhyolite domes occur in the Cerro Prieto region about 62 mi (100 km) south of the Salton Sea. There are also older volcanic outcrops in the Salton Trough dating between 3.3 and 3.5 mya, as well as some of the youngest obsidian in North America dating from ~2.5 mya.

About 5.5 mya, the Colorado River first began filling the Salton Trough, far north of where it meets the sea today, based on evidence from rocks of the Bouse Formation from Imperial Valley, Blyth, and Parker, and from the Hualapai Limestone Member of the Muddy Creek Formation near Lake Mead, and sedimentary layers in Anza Borrego State Park. This may have been about the same time the Colorado began to carve the Grand Canyon across the Kaibab plateau, although geologists still debate the timing of that event and some recent work suggests the canyon might be much older than previously thought (perhaps as old as 70 mya). By 4 mya, the river mouth had moved southward to the Yuma area.

Today, 2–4 mi (3–6 km) of Miocene and younger sediments overlie the oceanic-continental crust of the Salton Trough, which continues to subside at a rate of 1–2 millimeters/year (mm/yr). The impressive vertical dimensions of the Salton Trough can be appreciated by comparing Torro Peak near the north end of the Salton Sea, which rises 2658 meters above mean sea level, to the 6000 meter depth of basin fill in the valley; the relief in the basement rock itself is comparable to that of Mt. Everest! The lowest point in the Salton Trough today is the Salton Basin, which is 226 ft (69 m) below mean sea level. Laguna Salada, a western sub-basin of the Mexicali Valley, is 11 m below mean sea level. The only point in North America lower than the Salton Trough is Death Valley at 86 m below mean sea level.

The San Andreas-Gulf of California Fault System is the geologically “messy” boundary between the Pacific and North American Plates in this region of the world. Evidence suggests that at 1.5 mya the San Andreas Fault had an average displacement rate of ~35 mm/yr, decreasing to ~9 mm/yr about 90 thousand years ago, and increasing again to a present displacement rate of ~40–48 mm/yr. At this rate of relative movement, Los Angeles could be adjacent to San Francisco in about 15 million years, although southern California and the Baja California Peninsula will eventually become an island!

The oblique plate movements are causing the Gulf to open in a wedge-like fashion, with spreading occurring faster at its southern end, while the rift valley narrows in the north. The northern tip of this tectonic wedge currrently ends at San Gorgonio Pass, near Palm Springs, California. The San Andreas-Gulf of California Fault System comprises several transform faults, or “strike-slip faults,” which means that plate movements on either side are oblique to one another, in this case with predominantly lateral (sideways) motions. Thus, the spreading center in the Gulf does not form a straight line of troughs and ridges because both spreading and transform (angular) motions are occurring.

A map of the seafloor of the Gulf shows a zigzag series of parallel faults aligned with the motion of the Pacific Plate and separated by small deep troughs, which are perpendicular to the faults and are the sites of spreading and crustal formation. At its northern end, the Gulf spreading system becomes the rapidly subsiding Salton Trough—a northern continuation of the

Gulf—and the well-known San Andreas Fault System. In the broadest sense, the San Andreas Fault System runs from the Colorado River Delta to Point Reyes just north of San Francisco. In the north it continues offshore as a coastal submarine fault system all the way to the Mendocino Triple Junction where the Juan de Fuca, Pacific, and North American Plates meet off Cape Mendocino, California. In the south, the fault system extends beyond the mouth of the Gulf to where it joins the Rivera Triple Junction.

The spreading process under the Gulf's waters has resulted in both thinning of the Earth's crust and development of deep seafloor hydrothermal vents. These vents have probably been active since the Late Miocene and many persist today, such as those in the Guaymas Basin, Wagner Basin, and along the Alarcón Ridge, where geothermal liquids and gases discharge through fractures in seafloor rock and overlying sediments. Geothermal springs also occur intertidally and on land throughout the Gulf Extensional Province, primarily along active faults on the eastern coast of the Baja California Peninsula. At the small fishing camps of Coloradito and Puertecitos, just south of San Felipe, and in Bahía Concepción, small geothermal hot springs occur in the intertidal and shallow subtidal zones where people use them as a source of fresh water and for bathing (Endnote 6). The famous old Buena Vista Fishing Resort, between La Paz and Cape San Lucas, for many decades has used water from a geothermal spring that runs under the hotel. Certainly many geothermal springs remain to be discovered in the Gulf. These coastal springs discharge heated water (to 90º C) derived from a mix of rainwater and seawater. In the intertidal zone, no macroscopic invertebrates live in the immediate area of the hot discharge (which also has a somewhat low pH, ~6.2); barnacles may occur within 15 centimeters or so of the discharge, and other invertebrates begin to appear a bit farther away. In the northern Gulf, it has been anecdotally reported that endangered totoaba (*Totoaba macdonaldi*), a large fish in the croaker/corvina family (Sciaenidae), congregate around geothermal vents, and fishers illegally fish for them at those sites.

On the mainland coast in northwestern Mexico, surprisingly little uplift has accompanied the extensive horizontal movement over the past 6 million years, though there has been recent uplift of up to 150 m along the eastern margin of the Colorado River Delta, driven by the Cerro Prieto Fault. This uplift created the Mesa de Sonora, which probably elevated in the early to middle Pleistocene. Less dramatic uplifted Pleistocene beach terraces, 7–25 m above mean sea level, can be seen along the coast from El Golfo de Santa Clara southeastward to the Bahía Adair area, and also in the region between Guaymas and Puerto Lobos (Cabo Tepoca) in central Sonora. The age of the highest of these beach terraces—which seem to be homologous—might reflect an estimated 30,000 to 40,000

The San Andreas Fault begins near the delta of the Colorado River and runs northwestward into California (NASA image)

years-before-present (ybp) high sea-level stand, or might reflect an earlier interglacial shoreline present 125,000 ybp, and it is probably a combination of a high sea-level stand followed by a small amount of uplift. The unique Mesa de Sonora uplift is probably the result of drag-folding directly related to Cerro Prieto Fault activity beginning ~1 mya and continuing today. The Mesa de Sonora marine terrace, 50 to 150 m above mean sea level, was built during the Pleistocene as a result of episodic high sea-level stands and Colorado River alluviation. The marine terrace sands are Pleistocene fluvio-deltaic deposits, covered by younger, wind-driven eolian

The Colorado River Delta from space (NASA Earth Observatory image). Note the agricultural fields of the Mexicali Valley, the winding course of the Colorado River, the long straight Cerro Prieto Fault leading to the low basin of Ciénega Santa Clara, and southeast of the Ciénega the El Doctor Wetlands.

deposits that make up part of the Gran Desierto de Altar. The paleontologically rich El Golfo Badlands are on the Mesa de Sonora. Marine terraces are coastal landforms produced by littoral erosion during previous sea-level stands, and while these are common features of most coastlines, they are rare in the Gulf. Globally, these exposed traces of old beaches generally correspond to high sea-level stands of previous warm episodes or the glacial

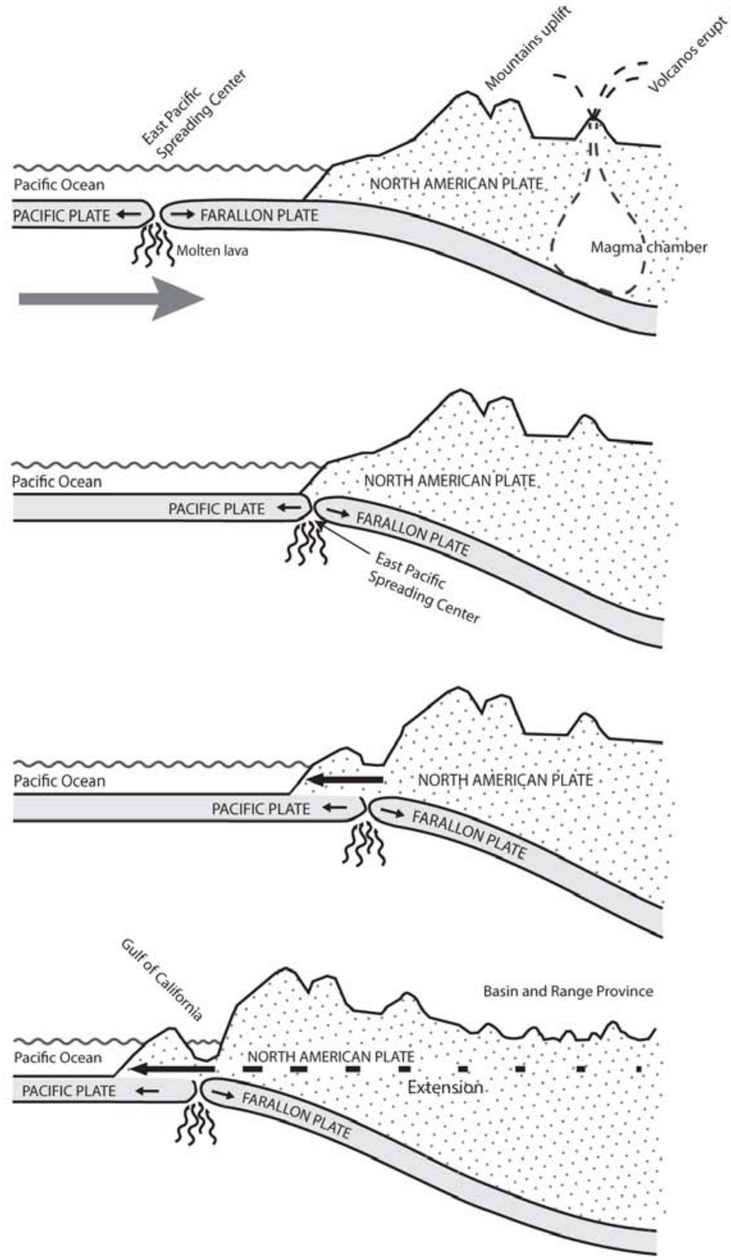
# MOUNTAIN BUILDING IN THE SOUTHWEST

***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 it 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).*

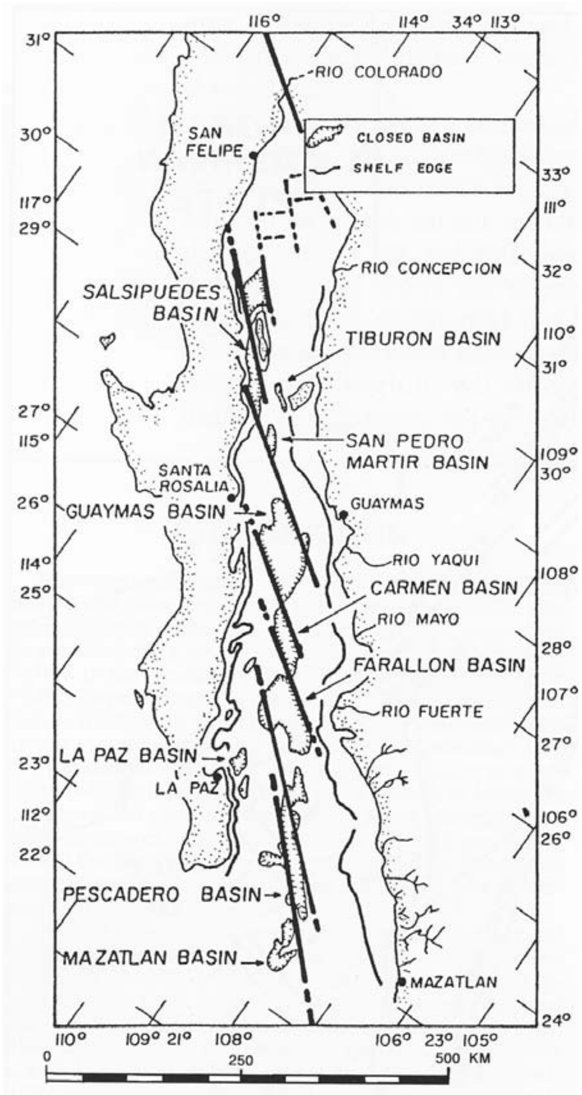
***b. About 45 million years ago:*** *The East Pacific spreading center meets the North American Plate and is "dragged" beneath it by the pull of the submerging Farallon Plate.*

***c. About 35 million years ago*** *(extensional phase): The East 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 this western margin of North America begins to move to the west with the Pacific Plate, it eventually opens a trough, shallow at first, but eventually deep enough that it fills with seawater to create the Gulf of California (d).*

***d. About 5.6 million years ago*** *(extensional phase): As the attached portion of the North American Plate is pulled to the west, the western half of the mainland continent is stretched and thinned, creating the widespread basin and range topography that includes the Madrean Sky Islands (see text for details). Today, the Baja California peninsula and south- ern half of California are still moving westward, attached to the Pacific Plate.*

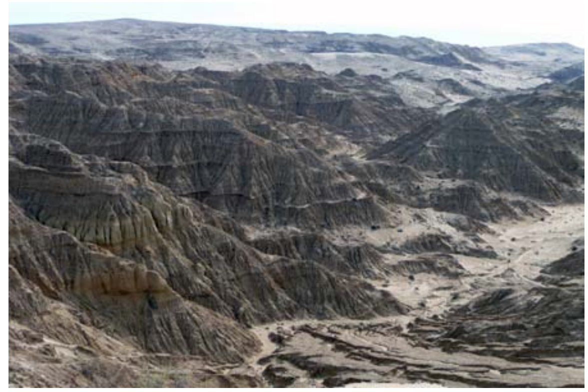



Mountain Building in the Southwest.  Concept development by R. Brusca and W. Moore; graphic design by Linda M. Brewer.




Tectonic map of the Gulf of California. Basins correspond to spreading centers bounded by active transform faults forming the San Andreas-Gulf of California Fault System. (From Suarez-Vidal et al., in Dauphin & Simoneit eds, 1991, The Gulf and Peninsular Province of the Californias. AAPG Mem. 47)

minima of the Quaternary. Three globally recognized terraces have been documented from the last interglacial period (known as stage IS 5), and are identified as substages 5e, 5c, and 5a, corresponding to ages of 125,000, 105,000, and 85,000 years, respectively. Calculating the elevation



The El Golfo Badlands, on the Mesa de Sonora, east of the fishing village of El Golfo de Santa Clara (Photo by R. Brusca)

of identified marine terraces above current sea level allows one to calculate how much coastal uplift has occurred. The IS 5e terrace/shoreline can be seen at a nearly constant elevation of 5–7 m between Bahía Adair and Guaymas, and seems to have had an uplift of no more than 1–2 m during the last 120,000 years. In cases where little or no uplift has occurred, it can be difficult to discern Pleistocene marine terraces.

In contrast to the generally low-relief Sonoran coast, steep relief and outcroppings of rocks of volcanic origin characterize the eastern Baja California Peninsula coastline. Here, uplift has been slow but continuous, ancient beach terraces are scattered along the peninsula, and the continental shelf is narrow. Along the Pacific coast of the United States and northwestern Mexico, only the 5e (125,000 ybp) terrace is well documented, although traces of what might be the 5c (105,000 ybp) terrace have also been seen. Mapping the 5e terrace around the Baja California Peninsula suggests that the mean rate of uplift has been ~10 centimeters/1000 years, with lower rates in the north and rates of up to 35 cm/1000 yrs in the south—although this rate has greatly diminished over the last tens of thousands of years. The four areas on the Baja California Peninsula showing evidence of the fastest rates of uplift are Santa Rosalía within the Gulf, the Vizcaíno Peninsula, the Punta Banda area south of Ensenada, and Cabo San Lucas. Punta Banda has at least 330 m of uplift (probably all Quaternary) and about 14 distinct stage 5e terraces almost regularly spaced vertically, with 25 m height differences between them.

Volcanic headlands on the coast of Sonora, such as the 15 million-year-old Punta Peñasco and nearby El Cerro Prieto ("Black Mountain") headlands, predate the opening of the Gulf and are remnants of ancient Middle Miocene interior volcanism.

As noted earlier, some writers have loosely used the term "Proto-Gulf" to refer to marine incursions or embayments that preceded the separation of the Baja California Peninsula from the mainland and the formation of the modern Gulf of California ~6 mya. The oldest marine incursion dates, based on localized outcrops and exploratory wells drilled in the northern Gulf, are Miocene and have been estimated at 13–9 mya. Some evidence also suggests a marine incursion reached beyond the Salton Trough, perhaps all the way to the Lake Mead/Needles area, and the San Gorgonio Pass, California, around 6.5 mya. Similar dates for a marine incursion have been reported from the San Felipe area (NE Baja California) and on Isla Tiburón. However, interpretations of these marine sedimentary and fossil strata are still being debated. Late Miocene (6.0 – 5.5 mya) diatom beds from the San Felipe area are perhaps the youngest fossil deposits that have been attributed to marine incursions; however, these might represent the early Gulf itself (or the dating might be inaccurate).

It is likely that several different Miocene incursions took place between 13–6 mya. Evidence suggests the possibility of both northern and southern incursions, the latter possibly occurring via what was to become the mouth of the Gulf or via a seaway somewhere north of the present Cabo San Lucas region. Northern marine incursions might have been via an inlet south of where the Sierra San Pedro Mártir stands today, perhaps around the present-day location of Bahía (Laguna) San Ignacio on the Pacific coast of the peninsula. Note, however, that the Sierra San Pedro Mártir is, like the other Peninsular Ranges, relatively young in age. The uplift of Sierra San Pedro Mártir probably began just after the Gulf opened ~5.5 mya, and its formation was tied directly to the same tectonic forces and extension that opened the Gulf and created the San Andreas Fault system. At an elevation of 3095 m (10,154 ft), the Picacho del Diablo of this range is the highest point on the Baja California Peninsula.

The putative inlets for these marine incursions have been confusingly referred to as "transpeninsular" seaways, although it is highly likely that the peninsula had not formed before 6 mya. Indeed, there is no good physical evidence of any true transpeninsular seaway across the Baja California Peninsula subsequent to the formation of the Gulf of California. Therefore, suggestions that present-day animals in the Gulf of California have a direct biogeographic (or genetic) descendency from a "Proto-Gulf" or from a "transpeninsualr seaway" are highly speculative at best.

Some workers have hypothesized a Miocene Gulf that extended well into southern California and then retreated to its present configuration during the Pleistocene, but current geological data do not support this early opening of the Gulf of California. Some biologists have interpreted breaks in mitochondrial DNA (mtDNA) between populations of small vertebrates on the Baja California Peninsula as evidence of a separation due to a Pleistocene transpeninsular seaway in the central Baja California Peninsula. However, there is no evidence of a sea-level rise sufficient to accommodate such complete transgressions over the past 6 mya—a 300 m rise, or more, would be required. So it would seem that other explanations for these genetic patterns should be sought. It could be that the genetic patterns were established earlier in the Miocene when the documented marine embayments could have driven

Cape Region of the Baja California Peninsula (NASA image)

vicariance/speciation events for coastal land vertebrates before the peninsula formed. Such vicariant patterns could then remain detectible on the peninsula subsequent to its establishment. Another possibility is that any of the well-known climatic or vegetation breaks that developed on the peninsula over the past 6 million years could have driven population divergences among small vertebrates. These climatic/weather patterns are recognized today in the biogeographic patterns of the plant communities on the peninsula. There are no strong data from marine organisms that support a transpeninsular seaway from the Pacific Ocean to the Gulf of California and, in fact, some molecular studies have found deep divergences that contradict putative seaways (e.g., Lin et al. 2009). (Endnote 7)

The low-lying Isla San Ildefonso, in the Sea of Cortez (Photo by R. Brusca)

The modern Gulf of California comprises an 800 mi (1300 km)-long peripheral extension of the eastern Pacific Ocean, varying from ~75 mi (120 km) wide at its mouth to ~30 mi (50 km) in the north, enclosing a marine surface area of ~82,000 $mi^2$ (210,000 $km^2$) and a shoreline of 4350 mi (7000 km), including island coastlines. The present Baja California Peninsula is 900 mi (1450 km) in length and covers 56,000 $mi^2$ (145,000 $km^2$)—38 percent of the peninsula's Gulf coastline is in the state of Baja California, 62 percent in the state of Baja California Sur.

Since the Gulf first began to form, numerous islands have broken off the peninsula and mainland. This could have been a consequence of either the extension process, or a product of faulting and uplift associated with tectonic activity along the many faults that arise off the East Pacific Rise and that today bisect the Gulf. These islands include Islas Salsipuedes, San Lorenzo Norte and Sur, Carmen, Danzante, Coronados, Monserrat, Santa Catalina, San José, and Espíritu Santo. Other Gulf islands are actually part of the mainland, separated by sea barriers only since the rise of sea level since the end of the last "ice age" (the Wisconsin Glacial) ~13,000 years ago—e.g., Alcatraz, Cholludo, Dátil, Patos, and the massive Isla Tiburón (at 472 sq mi, Tiburón is the largest island in North America south of Canada). It has been suggested that Islas Dátil and Cholludo, although now "attached" to southeastern Tiburón, are fragments of land that originally came from the Baja California Peninsula, that were torn off and left behind as the Gulf opened (see Oskin and Stock 2003).

Other islands arose from the seafloor and are the result of recent volcanism, including Islas San Esteban, San Pedro Mártir, San Pedro Nolasco, San Luis and Tortuga. The Santa Rosalía area has been particularly active volcanically. The writings of Jesuit father Ferdinando Consag date the most recent eruption of the Tres Virgenes Volcanos complex, located just north of the town of Santa Rosalía, as summer 1746. Isla San Luis was volcanically active as recently as ~1200 years ago, and remains potentially active today. Isla Coronados (near Loreto) was built on andesite flows dated between ~690,000 and 160,000 ybp, but it also has a younger 260-m high cone of an extinct volcano. Over 900 islands, islets, and emergent rocks have been identified in the Gulf's waters, making it one of the world's largest island archipelagos. The sizes, locations, and names of more than 230 of the named islands are given in Table 1.1 of Case et al.'s (2002) *A New Island Biogeography of the Sea of Cortés*. Many of the islets and rocks remain unnamed.

The high peaks of the Tres Virgenes loom in front of a setting sun, seen from San Carlos (Sonora), ~70 miles across the Gulf (Photo by R. Brusca)

**The Colorado River**

The area that is currently the Colorado Plateau had been near sea level prior to the Laramide Orogeny, as indicated by the thick marine sediment layers that blanket the region. These marine deposits are remnants of the great Cretaceous seaways that engulfed much of interior North America. The uplift of the Plateau was a major event in creating the present landscape of southwestern USA. Yet the timing of this uplift, from sea level to nearly 8000 ft (2415 m), remains one of the great unresolved mysteries in modern geology. Some researchers argue the uplift was recent, just in the past few million years. Others suggest it was much earlier, perhaps 35 million years ago. A similarly unresolved question is, where did all the water go that drained to the west off the Rocky Mountains once they had formed? If there is an abandoned river valley, that valley has not yet been found. If there was a huge inland lake west of the Rockies, that too remains undiscovered.

Further deepening the mystery of the Colorado is a 150-year debate about when the canyon itself was cut. The "young canyon" model suggests the gorge was carved just within the past 5 million years or so, whereas the "old canyon" hypothesis suggests a series of ancient rivers carved ancestral canyons along more or less the same route, perhaps as long as 150 milliion years ago. Most recently, researchers have found evidence that different parts of the canyon were carved at different times—a mixed age model of the canyon. One of the oldest canyon segments, the "Hurricane Segment" (named after a famed geolgical fault) lies in the eastern portion of the canyon, and it might be over 150 million years old. But, a section known as "Eastern Grand Canyon" (immediately downstream of where the Little Colorado River joins the Colorado) might not have begun to downcut until around 25 mya. And, finally, the westernmost and easernmost segments of the canyon were probalby largly carved in just the past 5 or 6 milion years. This mixed history model posits several ancient river canyons, at different times, that were eventually linked together (Endnote 8).

In any case, the topography of the *modern* Colorado River began with the Basin-and-Range faulting period, and by ~8 mya the Basin-and-Range landscape of the Southwest was basically established, setting the stage for the development of the mighty Colorado River as we know it today. By the middle Pliocene the Colorado River had achieved roughly its present-day course and had begun depositing its outflow and sediments into the northernmost region of the Salton Trough. The delta of the

Colorado River was probably far north of its present location ~5.5 mya, perhaps near today's Lake Mead. As sediments from the Colorado River filled the Salton Trough, the delta gradually moved southward. Around 4–3.5 mya, the head of the Gulf of California was probably somewhere near the cities of Blyth and Parker. At subsequent times, the Colorado River probably created alluvial sediment barriers at the head of the Gulf leading to the creation of giant freshwater lakes, but as these lakes grew they overflowed to again connect water flow to the upper Gulf. As deposited sediments built the delta, it progressed southward along the Salton Trough. This progression can be traced in the Bouse Formation record, in the stratigraphic record, and by mapping/dating archeological data.

Due to changes in the Colorado River's course, the modern Salton Trough has been flooded by river flow at least four times in just the past 7000 years, most recently in 1905 due to human actions that created the modern Salton Sea (Endnote 9). The old Colorado River sediments contain fossil foraminiferan shells washed out of the Mancos Shale (late Cretaceous) of the Colorado Plateau, and the delta itself contains a record of the erosion of its source rocks from the Grand Canyon and Colorado Plateau. Today, more than 3000 m of Pleistocene deltaic and marine sediments point to a long-term, mainly tectonic subsidence of the delta region, while an elevation (sill) of about 12 feet is all that separates the Salton Trough from the Gulf of California.

The Lower Colorado River Basin from space (NASA image)

The current configuration of the Colorado River Delta was formed during the Holocene by a combination of sea-level rise, tectonism, and deltaic deposition. During low sea-level stands in the Pleistocene, the Colorado River probably emptied its sediment directly into the Wagner Basin of the northern Gulf. In contrast, during high sea-level stands in the Pleistocene, occurring during interglacial periods, the Colorado River flowed just east of the Cerro Prieto Fault to empty into the Gulf near the present town of El Golfo de Santa Clara, or perhaps farther south at Bahía Adaír.
Today, the Colorado River runs a course approximately 1430 mi (2300 km) long, from the Rocky Mountains to the Gulf. The delta, now largely ecologically destroyed by lack of river flow (due to dams and diversions in the United States), is one of the harshest environments in North America, wtih an average annual rainfall of just 2.7 inches (6.8 cm) and surface tidal-flat temperatures

ranging from ~3º C in the winter to ~40º C in the summer.

Before the damming of the Colorado River, its freshwater influence could be seen as far south as San Felipe (Baja California). Today, with the river's flow nearly absent altogether, tidal-flat infaunal biodiversity is lower than in the past, dominated by a few dozen species of molluscs (most abundant are the snail *Nassarius moestus*, and the clams *Tellina meropsis*, *Donax navicula*, *Chione fluctifraga* and *C. pulicardia*, and *Tagelus affinis*), as well as the brachiopod *Glottidia palmeri* and the small sand dollar *Mellita longifissa*. The small clam, *Mulinia coloradoensis*, once very abundant in the upper Gulf, is today restricted to a few sites at the river's mouth (including Isla Montague, which is also one of only two sites where Elegant Terns breed, the other being Isla Rasa in the upper-central Gulf). (10)

The Mexicali Valley portion of the Salton Trough extends to the southeast beneath the great sand sea of the Gran Desierto de Altar, as the Altar Basin. The Altar Basin is framed between the Cerro Prieto Fault and Sierra del Rosario (610 m in height), and between the city of San Luis Río Colorado and Bahía Adaír. The Cerro Prieto Fault is active at the plate boundary today, and it forms the western structural boundary of the Altar Basin. It also is transitional between the San Andreas fault system to the north, and the East Pacific Rise in the Gulf of Claifornia to the south. Cerro Prieto itself is actually a small volcano, a 233 m-high dacitic lava dome in the middle of the Cerro Prieto geothermal field, 33 km south of the U.S.-Mexico border. In the center of the dome is a 200 m-wide crater. The dome was formed druing a series of events between 100,000 and 10,000 years ago.

Like the Imperial and Mexicali Valleys, the Altar Basin shows evidence of the same cycle of: (1) late Miocene extension and subsidence, (2) marine transgression and flooding, and (3) basin filling largely dominated by the growth of the Colorado River Delta and, to a lesser extent, by alluvial deposits. The formation of the Colorado River Delta effectively isolated the Altar Basin from other basins located to the north and west within the Salton Trough. The Altar Basin became inactive as a result of the westward shift in the locus of tectonic activity from the Altar Fault to the Cerro Prieto Fault, coupled with realignments in the course of the Colorado River during the Pleistocene. This basin is no longer part of the active delta but instead is an expanse of eolian sand dunes that comprises the northernmost extent of the Gran Desierto de Altar. Exploratory wells in the Altar Basin reveal beautiful sequences of regional geologic history, including: (1) late Cretaceous to early Tertiary granitic and metamorphic basement rocks, overlain by (2) late Miocene-early Pliocene marine shales resulting from a pre-Gulf of California marine incursion, with these overlain by (3) interbedded marine/deltaic sandstones/mudstones/siltstones representing the arrival of the Colorado

River Delta 5.3–4.2 mya, and finally (4) a Pliocene-Pleistocene mix of marine-Colorado River Delta coarse-grained, poorly consolidated sandstones covered by the cap of sand dunes.

Greatly weathered, highly calcareous sandstone formation at Pelican Point, near Puerto Peñasco ("Rocky Point"), Sonora (Photo by R. Brusca)

In contrast to the Altar Basin, Laguna Salada (to the west) is an example of a still-active basin in the southern Salton Trough. The low-lying (11 m below mean sea level) Laguna Salada is separated from the Mexicali Valley by the low Sierra Cucapa-Sierra El Mayor mountain range (on the east), and bounded by Baja's massive Sierra Juárez mountains on the west. The Laguna Salada Fault (part of the southern San Andreas Fault System) runs along the eastern margin of the laguna (the western margin of the Sierra Cucapa-El Mayor range) and the Sierra Juárez Fault is on the west side of the laguna. The placement of the fault is easily seen by surface features, such as fault scarps, displaced alluvial fans, and exposed bedrock. Visible, young alluvial deposits were probably displaced in large 1892 and 2008 earthquakes. The basin itself is filled with 2.5–3.7 mi (4–6 km) of fill deposits.

The Pleistocene ecological history of the Colorado River is recorded in the fluvial sediments of the Mesa Arenosa (near the city of Mexicali) and Mesa de Sonora (near the town of El Golfo de Santa Clara), and on the exposed 500 to 2700 m-thick sandstones and siltstones of the El Golfo Badlands. Located in the southwestern Altar Basin, the El Golfo Badlands are located just east of the Cerro Prieto Fault zone on an alluvial terrace uplifted as much as 130 m, and are interspersed with erosional ravines revealing ancient delta remains. Although the Altar Fault was probably once the main plate boundary, that boundary shifted westward to the Cerro Prieto Fault some time during the Pliocene. The Altar Fault is no longer seismically active.

Northwest of the town of El Golfo de Santa Clara, the Cerro Prieto Fault runs along the eastern margin of the Ciénega Santa Clara. Middle Pleistocene movements along the Cerro Prieto Fault probably caused the 150 m uplift of Mesa Arenosa (in the Mexicali Valley), which in turn caused the migration of the Colorado River westward. Mesa Arenosa is a rotated up-faulted block that has experienced more than 150 m of uplift during the Quaternary. This uplift, coupled with sea-level fluctuations, has resulted in formation of a series of beach terraces along the Sonoran coast of the upper Gulf.

The Ciénega Santa Clara (Photo by R. Brusca)

The El Golfo Badlands cover 62 $mi^2$ (160 $km^2$) on the elevated Mesa de Sonora east of El Golfo de Santa Clara. Here vertebrate and land plant fossils originating 1.9–0.4 mya reveal an ancient riparian ecological history. More than 40 species of vertebrates have been found in these fossil deposits, including many tropical species, temperate species, and many species that are now extinct. All were freshwater/riparian or terrestrial upland forms. Among these are four species of New World horses, three camels, a mammoth, giant tortoise, boa constrictor, flamingo, giant anteater, hyena, and "cave bear" (Endnote 11). Rocks in the El Golfo Badlands also reveal their Colorado Plateau source, including late Paleozoic invertebrate and protist fossils eroded from the Colorado Plateau's ancient seabed formations. Beneath these freshwater deposits lie evidence of a Miocene marine embayment that had invaded the area much earlier.

The Cerro Prieto Fault channels underground water to create a series of freshwater springs, or *pozos*, called the El Doctor Wetlands (just north of El Golfo de Santa Clara). These wetlands are a tiny refuge for the desert pupfish, which once had a broader range within the now largely dry Colorado River freshwater wetlands. Prior to the volcanism of the Sierra Pinacate and the subsequent deflection of the Río Sonoyta to the east and south, the desert pupfish probably also had freshwater connections with the pupfish of the Río Sonoyta and Quitobaquito Springs of Organ Pipe Cactus National Monument.

El Doctor springs at ground level (Photo by R. Brusca)

Throughout the Bahía Adaír coastal region, isolated pozos are present between El Golfo de Santa Clara and Puerto Peñasco (e.g., El Tornillal with its screwbean mesquite grove, La Salina with its massive salt deposits, etc.). These pozos are probably all within a day's walk of one another, which must have been convenient for Native American inhabitants of the region. All of the pozos are surrounded by prehistoric, human-deposited shell middens (called *conchales* or *concheros* in Mexico). The source of water upwelling in the pozos is uncertain but seems likely to be a shallow aquifer originating from the north and east, carrying Colorado River water plus rainwater from the Cabeza Prieta region, and also some rain capture from the Sierra Pinacate.

Aerial view of El Doctor freshwater springs (pozos)

To the east of the delta/upper Gulf region is the Gran Desierto de Altar, a Pleistocene sand sea that covers 2200 $mi^2$ (5700 $km^2$), positioned between the Colorado River on the west and the Sierra Pinacate on the east. This is the largest area of active sand dunes in North America, with some dunes reaching more than 200 m in height. Three wind-captured sand sources have been identified for the sand of the Gran Desierto: (1) deltaic sediments of the Colorado River, (2) beach sands from the upper Gulf and Bahía Adaír, and (3) erosion of the granitic mountains in the region. The first two sand sources dominate due to prevailing winds from the west (in the summer) and northwest (in the winter). The northernmost dunes (the Algodones Dunes of the Yuma area) are rich in quartz and have their

Shell midden, Estero El Soldado, near San Carlos, Sonora (Photo by R. Brusca)

Shell midden, Isla Espíritu Santo, southern Gulf (Photo by R. Brusca)

primary origin in eroded sands from the Colorado River, whereas the more southern dunes (in Sonora) are dominated by shell fragments and have their origin primarily in beach sands of the delta region. Thus the dunes of the Gran Desierto represent the erosional remains of the Grand Canyon and Colorado River and it's delta. Travelers on U.S. Intersate 8 don't even need to get out of their car to see the magnificent Algodones Dunes, the steep face on the side of each dune pointing northwest, into the prevailing wind direction. (Endnote 12)

The entire Gran Desierto dune field is probably less than 25,000 years old and perhaps as young as 12,000 years, although active eolian sand transport has greatly decreased since the end of the last glacial period ~12,000 years ago, when sea level was much lower and more upper Gulf sediments were exposed. Sea levels in the Gulf have been more-or-less stable for the last 6000 years. (Endnote 13)

**The Upper Gulf of California**

From the delta southward throughout the upper Gulf, the Sonoran coastline has many shallow coastal marine lagoons, or *esteros*. Both active and extinct esteros are present, the latter represented by low, flat-bottomed "salt pans" located just inland from the coast. In Mexico, these are usually called *playas*, but they are also known as *sabkhas*, a transliteration of the Arabic word for "salt flat." The active, hypersaline esteros empty almost completely with each low tide. The extreme tides of the upper Gulf, combined with the gently sloping shoreline, create extensive tidal flats where up to several (linear) miles of mud/sand flat are exposed during the ebb of spring tides. In fact, the bottom gradient is so gentle in the upper Gulf that lowering of sea level during the peak of the last glaciation (23,000–12,000 ybp) would have placed the shoreline ~30 mi (50 km) farther offshore than today. Many of the coastal salt pans, or *playas*, including some that are still inundated by the highest tides, form evaporative basins where salts have accumulated for millennia. Some of these salt pans, such as Salina Grande, have been harvested commercially for their salt. (Endnote 14)

The Sierra Pinacate volcanic field and adjacent Gran Desierto de Altar sand dune field, with the large Bahía Adaír below (NASA image)

Salina Grande and several other salt pans in the area have pozos in or next to them, and these natural springs create freshwater or brackish water-emergent "islands" in or adjacent to the salt deposits. The freshwater "islands" typically support stands of vegetation not seen elsewhere in the region, representing refugial pockets of ancient Colorado River riparian flora including screwbean mesquite, bulrush, yerba mansa, and other species. Most of the salt pans fill with available rainwater and become short-lived shallow "lakes," mainly in the summer monsoon season. These are often red in color due to halophilic archaeobacteria such as *Halobacterium*, or the reddish-colored green alga *Dunaliella salina*. The number of esteros decreases moving down the Gulf coast of the Baja California Peninsula, especially south of San Felipe, due to the increasing steepness of this more mountainous coastline.

Salina Grande, and one of its larger freshwater pozos (Photo by R. Brusca)

From northern Bahía Adaír to Desemboque de los Seris (aka Desemboque del Río San Ignacio) and Punta Tepopa on the Sonoran coast, and from San Felipe to Coloradito on the Baja California Peninsula coast, there are outcrops of beachrock. In geological terms, beachrock is defined as “lithified littoral sediments,” and it is most common in arid regions of the world. In some areas, such as the Florida coast, it is composed primarily of sand. In the upper Gulf of California it is composed of beach sand, mollusc shells, and sometimes small-to-large rocks. When shells are included in the calcified matrix, beachrock is often called *coquina*. The precipitated calcium carbonate that cements this material together comes both from the sea water and from the dissolving shells themselves. Coquina outcrops have been traced to 7.8 mi (12.5 km) east of Puerto Peñasco (“Rocky Point”), in the shallow subtidal region or buried under intertidal sands. Some of the outcrops east of Puerto Peñasco include boulders more than a meter in diameter.

Salina Grande; a large expanse of crystallized salt (Photo by R. Brusca)

Paleontologists have assigned a Pleistocene age to these upper Gulf coquinas, and uranium-thorium dating has estimated an age of ~130,000 ybp (IS 5e). Elevated coquina deposits north of Bahía Adair are the same age as those at Puerto Peñasco. One form is high in *Chione* clam shells (the “*Chione* coquina”) and is considered an index bed. *Chione* coquina occurs at an elevation of 23 m above mean sea level at Punta Gorda, and at 10–12 m above mean sea level between Punta Gorda and Bahía Adair. Other scattered Pleistocene outcrops occur along both coastlines of the upper Gulf. All of the mollusc species in these deposits still live in the Gulf today.

Estero el Soldado, a nearly pristine mangrove lagoon near Guaymas-San Carlos, Sonora (Photo by R. Brusca)

Working in the Puerto Peñasco area in the 1950s and 1960s, Ronald Ives reported possible remains of three distinct shorelines, one a few meters above mean sea level, another at 23 m above mean sea level (his "*Chione cancellata* shoreline), and the third at 60–90 m above mean sea level (his "*Turritella* shoreline"). Later work showed the two higher "shorelines" to be misinterpreted eolian sands or artificial accumulations of marine shells placed there by animals or prehistoric peoples. Ives' lowest shoreline, at ~7 m above mean sea level in this area, represents the IS 5e shoreline. Thirty miles southeast of El Golfo de Santa Clara, at the headland of Punta Borrascosa, an ancient uplifted seabed holds hundreds of thousands of fossilized sand dollars (*Encope grandis*, *Encope micropora*, and *Mellita* [*M. grantii*?]), ghost shrimp burrows (*Thalassinoides* sp. or *Ophiomorpha* sp.), and *Chione gnidia*, documenting a Pleistocene (~125,000 ybp) seafloor habitat.

Coquina beachrock, Puerto Peñasco, Sonora (Photo by R. Brusca)

**The Sierra Pinacate and Gran Desierto de Altar**

> *Travel within the Pinacate region is slow, uncomfortable and sometimes hazardous. None of the region's waterholes are permanent. Visibility is poor throughout much of the year due to a dust haze, often made worse by a pall of smoke effluent which drifts south over the area from the smelter located at Ajo, Arizona. Heat shimmer and both hot and cold air mirages then further compicate visibility. Due to localized magnetic attractions in the region's lava flows, navigation or triangulation sightings by compass are unreliable*.
> Larry A. May, 1973, MSc Thesis

The Gran Desierto and El Pinacate mountain range (the Sierra Pinacate) comprise a UNESCO and Mexico-designated Biosphere Reserve, as well as a U.N. World Heritage Site (the last designation given in 2013)—the *Reserva de la Biosfera El Pinacate y Gran Desierto de Altar*. The Sierra Pinacate and the Gran Desierto lie east of the Cerro Prieto Fault and East Pacific Rise, so are part of the North American Plate.

The Gran Desierto is the largest active sand dune field in the New World, covering

1.4 million acres (5700 $km^2$ or 570,000 hectares). Although the age of this giant dune field is relatively young (12,000–25,000 years), the sands themselves, mostly from the Colorado River Delta, are much older. The Colorado River began depositing its sediments at the north end of the Salton Basin around 5.6 mya, and the delta had reached the Yuma area by ~4 mya. So the oldest sands in the Gran Desierto could be of these ages. The current position of the delta is probably 1–3 million years in age, and most of the Gran Desierto's sands fall into this age class.

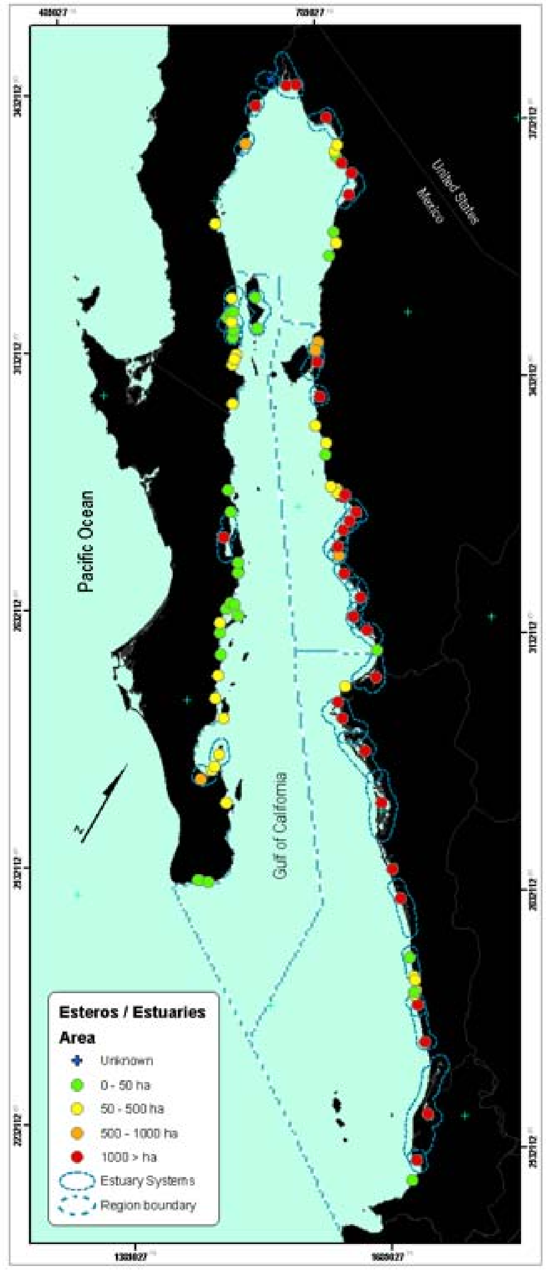
Coquina beachrock at Punta Tepopa, near Desemboque de los Seris, Sonora. (Photo by Cathy Marlett)

The Sierra Pinacate dates to ~1.3 mya, and began as Volcán Santa Clara, a single shield volcano that expanded in size with successive eruptions from a central vent complex 1.7–1.1 mya, although some geologists suggest the shield volcano could have originated 4–3 mya. Smaller basaltic/cinder cones and lava flows erupted on the slopes of Volcán Santa Clara and today extend out into the surrounding desert to bury the eastern periphery of the Gran Desierto sand dune field. The youngest of the flows probably took place just 8000 to 16,000 years ago, which opens the possibility that early Native Americans could have witnessed them! The largest lava flow visible today is the Ives Flow, dated at around 13,000 ybp, which covers 30 $mi^2$ (75 $km^s$) on the south flank of the main volcano and wraps around the northern end of the Sierra Blanca. Sierra Blanca and Sierra el Rosario are the only ranges within the Pinacate region that are not part of the volcanic history of El Pinacate—they are "outpost" Basin-and-Range geological formations (the Sierra el Rosario, northwest of the Sierra Pinacate, is probably the westernmost Basin-and-Range mountain in North America). The lighter-colored igneous rocks of the Sierras Blanca and el Rosario stand out in contrast to the surrounding dark volcanic ranges. Almost no Paleozoic rocks appear to crop out in the Gran Desierto.

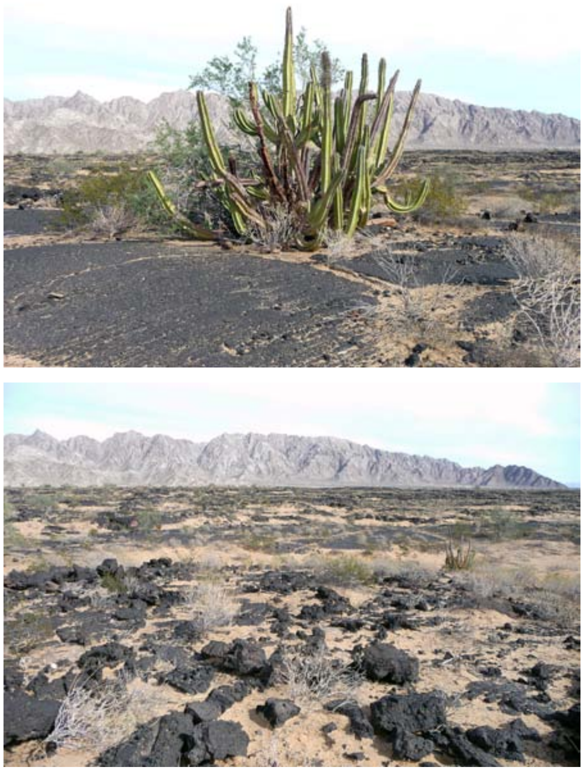
The Sierra Pinacate is thought to be the result of a small, shallow continental plate hotspot. Classic hotspots are believed to be very deep-rooted mantle plumes, and most are known from ocean basins (although another famous continental hotspot is the Yellowstone Hotspot, in Yellowstone National Park). One of the most intensively studied hotspots in the world is the one that created (and continues to create) the Hawaiian Islands chain. In fact, that hotspot is responsible for creating the world's tallest mountain, Mauna Kea, on the island of Hawaii. Although Mt. Everest reaches higher into the atmosphere (29,035 ft above sea level) than any other mountain on Earth, it is not the tallest because it begins its rise in the Himalayas at 19,160 ft, giving it an actual height of just 9,875 ft. The tallest mountain on Earth is Mauna Kea, which rises from a depth of 18,000 ft (on the seafloor) to 13,796 ft above sea level, a total height of 32,696 ft! Birds fly and whales swim, on the slopes of Mauna Kea

Hotspots contrast with spreading centers where magma genesis occurs at much shallower depths. James Gutmann and his colleagues have reported great differences between Pinacate lavas and the lavas extruded from the spreading center in the southern Gulf of California, and in 2008 they proposed that the Pinacate originated due to a "mini-plume" of upwelling material near to but quite distinct from the spreading center nearby in the Gulf. They regard Pinacate volcanism as related to Basin-and-Range basaltic volcanic fields (as opposed to its reflecting a failed rift of the East Pacific Rift Zone, as some have suggested).

Today, the Pinacate volcanic field covers over 770 mi$^2$ (2000 km$^2$) and is one of the youngest and most spectacular lava fields in North America. It encompasses around 500 eruptive centers, including nearly 400 cinder cones. Some cones have multiple lava flows, such as the seven distinct flows of Volcán Tecolote. The 10 or 11 explosive




Summary map of wetlands in the Gulf of California (from Brusca et al., 2006, Gulf of California Esteros and Estuaries. Analysis, State of Knowledge and Conservation Priority Recommendations. Report to the David & Lucile Packard Foundation)



Ives lava flow, with the Sierra Blanca in background, Pinacates (Photos by R. Brusca)

Tecolote Crater, Pinacates (Photo by R. Brusca)

craters in the Sierra Pinacate are special features called *maar* craters. Maar craters are created by enormous blasts of steam generated when underground magma interacts with shallow ground water. Most of the maar craters in the Sierra Pinacate are aligned along an east-west line located north of Volcán Santa Clara. This alignment roughly parallels the U.S.-Mexico border in the northern part of the biosphere reserve, along what might have been the old Río Sonoyta flow path. It has been suggested that groundwater under the old Río Sonoyta was responsible for the creation of the maar craters. The original delta of the Río Sonoyta might have periodically shifted its location between the El Golfo de Santa Clara region and the northernmost end of Bahía Adair.

The three largest maar craters in the world are found here: El Elegante, MacDougal, and Sykes Craters. The spectacular El Elegante Crater is 1200 m across and 250 m deep. During the last glacial period, perhaps as recently as 20,000 years ago, there was a lake in the bottom of Elegante Crater.

Cerro Colorado, Pinacates (Photo by R. Brusca)

The old flow path of the Río Sonoyta was likely deflected by the creation of the Sierra Pinacate, directing water flow southward to the Gulf of California just southeast of Puerto Peñasco—athough its water flows reaching the Gulf have been rare in the last 100 years and associated only with very wet years. Archaeological data suggest that before 1500 years ago, at least during wet

Elegante Crater, Pinacates (Photo by R. Brusca)

periods, the Río Sonoyta probably had a perennial flow to the coast southeast of Puerto Peñasco, where it formed the Estero Morua-Estero La Pinta coastal lagoon complex. This estero complex—which is probably less than one million years old—was more-or-less continuously visited (and perhaps even inhabited) by Native Americans 3500 years ago, and probably earlier. The Río Sonoyta still has a subsurface flow to Estero La Pinta (visible as vegetation patterns in satellite photographs). And, as recently as the early 1970s the river frequently had perennial surface flow years as far south as the Batamote Hills.

The formation of the Sierra Pinacate that disconnected the Río Sonoyta from the Colorado River Delta was apparently a vicariant event that led to disjunct populations of aquatic species such as the Río Sonoyta/Quitobaquito and the Lower Colorado River desert pupfishes (*Cyprinodon eremus* and *Cyprinodon macularius*), as well as populations of longfin dace (*Agosia chrysogaster*), Gila topminnow (*Poeciliopsis occidentalis*), and Sonoran mud turtle (*Kinosternon sonoriense longifemorale*). Longfin dace and mud

La Laja cone and lava flow, Pinacates (Photo by R. Brusca)

turtles are rare or absent in the delta area today due to regional drying resulting from over extraction of Colorado River water in the United States. Molecular dating places the age of separation of the two pupfish species at about the same age as the formation of the Sierra Pinacate, ~1.3 mya.

**Rocks That Tell Stories**

Given our understanding of the geological history of northwestern Mexico, the exposed coastal rocks around the Gulf of California reveal their origins and provide us with glimpses into the past. Rocks along the Gulf's coastline can be divided into several main types: intrusive igneous rocks, such as granite and diorite; extrusive igneous rocks, such as basalt, andesite, rhyolite and dacite; rocks composed of consolidated volcanic ash, such as tuff and welded tuff; limestones ("white rocks"); and sedimentary rocks, such as sandstone and beach rock. In the

In many of the Pinacate lava flows one can find small labradorite crystals that have washed out of the lava, or that remain embedded in the rock. Labradorite occurs in igneous rocks that are high in magnesium and iron silicates. (Photo by R. Brusca)

Namesake for the region, the Pinacate beetle, *Eleodes armata*, is a common tenebrionid in the area (Photo by R. Brusca)

Gulf region this classification is strongly correlated with geologic age and rock origin, so recognizing rock types along the shore quickly sheds light on the geological history of the area.

Along Gulf shorelines, igneous rocks such as granites and diorites are the oldest rocks encountered. They formed deep in the Earth, later to be uplifted by tectonic action and exposed by erosion. The famous sea arches of Cabo San Lucas, at the tip of the Baja California Peninsula, are composed of Cretaceous granites. The tilted granitic fault blocks that comprise the Sierra Juárez and Sierra San Pedro Mártir in northern Baja California, and the Sierra La Laguna of the Cabo San Lucas region, are also Cretaceous in origin. The well-known rocky point called Punta Pelícano, near Puerto Peñasco, Sonora, is 80–100 million-year-old diorite (Endnote 15).

Sierra Blanca, Pinacate Region (Photo by R. Brusca)

Sand dunes of the Gran Desierto de Altar
(Photo by Rick Westtcott)

Land's End–Cabo San Lucas, at the southern tip of the Baja California Peninsula (Photo by R. Brusca)

Andesites and the other extrusive (surface-formed) volcanic rocks date from the Miocene or younger, and are largely products of the submergence of the Farallon Plate beneath North America. Andesites, rhyolites, and basalts in the Gulf formed throughout most of the Miocene, 25 to 5 mya, as they were deposited in volcanic surface flows. The andesites, rhyolites and dacites of northwestern Mexico are punctuated by other volcanic rocks, such as breccias and tuffs. Reddish andesites and rhyolites, and yellowish tuffs, form some of the most colorful and beautifully weathered formations seen along Gulf coastlines and in nearshore eroded canyons. These layers were faulted and exposed during the tectonic events leading to the rifting of the Baja California Peninsula from the mainland, and most of the coastal cliffs of the Baja California Peninsula are composed of andesite. The dominant coastal rock type found on the islands of the Gulf is andesite, although some granitic islands (e.g. Santa Catalina) also occur, especially in the southern Gulf. Isla Espíritu Santo is interesting because the eastern side is composed of granodiorite, whereas its western side is largely exposed andesite layers.

Biogenic marine carbonate rocks (usually limestone, $CaCO_3$) in the Gulf region were formed in the Pliocene and Pleistocene, mostly during ancient marine incursions brought about by high sea-level stands between 5.6 and 1.8 mya. Sea-level retreats and coastal uplifts have subsequently exposed these ancient marine

Red rhyolite rocks embedded in yellowish tuff, Nacapule Canyon, San Carlos, Sonora (Photo by R. Brusca) beds. Limestone deposits can form from benthic accumlations of plankton skeletons (e.g., coccolithophores, foramini-ferans),calcium carbonate-secreting red algae such as rhodoliths (unattached, spherical algae resembling coral that accumulate on shallow sea floors), coral skeletons, and even stromatolites. Living rhodolith beds occur at a variety of locations in the Gulf today, especially in the warmer waters of central and southern Baja's eastern coast.

During the Pliocene, some of the large islands—including San José, Monserrat, Carmen, and Ángel de la Guarda—accumulated shallow limestone deposits that are now exposed as a result of coastal wave erosion. The southern Gulf islands have much more limestone than the northern islands. One of the most extensive limestone deposits in the Gulf occurs on the eastern side of Isla Carmen, where more than 15 mi (25 km) of Pliocene limestone coast (in discontinuous segments) is exposed in old Pleistocene beach terraces. Smaller marine coastal incursions associated with high sea-level stands during the Pleistocene are often demarcated by localized carbonate deposits. A 120,000–125,000 ybp fossil coral reef now stands 12 m above sea level on the southern end of Isla Coronados (near Loreto). However, there are no coralline-sand beaches on Isla Coronados, so if they existed in the past they have since been replaced. Fossil coral formations 144,000 years in age can also be seen on the wave-cut terrace of Baja's Cerro El Sombrerito, the easily-recognized hill at the mouth of the Mulegé River (the Río Santa Rosalía); the core of the hill is actually an ancient igneous plug from the eroded chamber of a former volcano. A 75 m-long fossil bed of silica carbonate, formed by stromatolites, has been described from Bahía Concepción.

Today, 18 hermatypic (reef-building) coral species occur in the Gulf of California, between Cabo San Lucas and the Colorado River Delta: 5 species of *Pocillopora*, 4 species of *Psammocora*, 3 *Pavona*, 3 *Fungia*, 2 *Porites*, and one species of *Leptoseris*. In the northern Gulf an encrusting form of *Porites californica* predominates and does not build reefs, but south of Isla Tiburon (28º N) a massive and columnar variety of *P. californica* predominates and occasionally contributes to reefs and reef-like formations. The only true coral reef that occurs in the Gulf today is at Baja's Cabo Pumo (23º 44' N), although small patch reefs can be found in Bahía San Gabriel on Isla Espíritu Santo.

The Gulf's modern coral fauna is mostly derived from the western Pacific, the original Caribbean-derived coral fauna having largely gone extinct subsequent to the closure of the Panamanian Seaway, either around 15 or 2.6 mya—geologists are still debating this timing. When plate movements in Middle America closed the great Panamanian Seaway, sealing it off and breaking the ancient Atlantic-Pacific Ocean connection (while simultaneously initiating a land connection between South

America and Central America), circulation in the western North Atlantic and Eastern Pacific Oceans changed dramatically, likely causing sea surface (and atmospheric) temperatures to also change. If the younger date (2.6 mya) is correct, these changes were possibly responsible for the initiation of the Pleistocene glacial cycles, which began about that time and have had a periodicity of about 100,000 years.

Endnotes

ENDNOTE 1. Together, the Earth's crust and uppermost mantle form a global-scale mobile layer known as the lithosphere that "floats" atop the rest of the mantle. The Earth's lithosphere is broken into a number of huge pieces, or plates. When lithospheric plates move apart, the gap between them—known as a rift—fills with new molten crustal material from below, a process that occurs on both oceanic and continental crusts (divergent, or "constructive" plate margins). For example, the Great African Rift Valley in eastern Africa is a location of active continental rifting and volcanic activity. When two plates meet, the heavier one tends to subduct—or thrust—beneath the lighter one. Oceanic plates are usually denser and heavier than continental plates, and consequently they typically subduct beneath continental plates. For example, the Pacific Plate is subducting beneath continental Asia near Japan (a convergent, or "destructive" plate margins); the associated melting of the subducted oceanic plate has formed the Japanese islands and accounts for the still-active volcanism in that area. Plates can also move past one another in opposing directions, sliding and shearing along fault lines that parallel the line of motion of the plates. In these cases ("conservative plate margins"), though the bulk of the plates continue moving inexorably in opposing directions, the plate margins sometimes temporarily "stick" along the faults. Such transform faults become sites of huge stresses in the Earth's crust. Earthquakes occur when such plate boundaries inevitably snap apart and the respective plates jolt into new positions. Earthquake epicenters are used to map the location of such faults. The San Andreas-Gulf of California Fault System represents such a boundary between the Pacific Plate and the North American Plate, where these massive plates incrementally shear past one another.

ENDNOTE 2. North of Mexico, the subduction of the Farallon Plate caused an episode of intense volcanism (40-20 mya) that covered much of the land that was eventually to become the Basin-and-Range Province. Today, these middle Tertiary rocks are widespread throughout the Basin-and-Range Province, and in Arizona they provide the backdrop for some of the region's most scenic areas, including: Picacho Peak; the Kofa National Wildlife Refuge; Organ Pipe Cactus National Monument; Apache Leap (near Superior); and the Chiricahua, Galiuro, Superstition, and Hieroglyphic Mountains.

ENDNOTE 3. The course of the Colorado River below Grand Wash and the site of Hoover Dam was established post-6 mya and pre-4.8 to 4.3 mya (Howard and Bohannon 2001). This age interval might mark the time when the upper Colorado River integrated its course to that of the lower Colorado, so drainage from the Rocky Mountains reached the Gulf of California and dramatically increased the sediment supply and the growth rate of the delta.

ENDNOTE 4. Although most research seems to support a date of 6.0 mya for the opening of the Gulf, older dates in the range of 10-12.5 mya have also been proposed (e.g., Gans 1997). Currently, these two extremes remain unresolved. However, it is important to remember that the initiation of spreading after the establishment of the contemporary plate boundary is not necessarily the same thing as the date of inundation of the basin by Pacific Ocean waters (i.e., spreading initiation did not necessarily immediately lead to establishment of the marine Gulf of California). Further, no spreading center in the Gulf has been dated older than 6 mya.

ENDNOTE 5. The eastern wall of the Salton Trough is the southern San Andreas Fault. The western wall consists of plutonic rocks of the Peninsular Ranges, including the San Jacinto, Santa Rosa, Agua Tibia, and Laguna Mountains in the United States and the Sierra Juárez Mountains in Baja California. Near the southern end of the Salton Sea, the San Andreas Fault system appears to terminate in a transform fault at a spreading center called the Brawley Seismic Zone. This is the most northern of the long series of spreading centers distributed along the length of the Gulf of California. The proximity of this northernmost spreading center accounts for the abundant young volcanic and geothermal features in the area, including the Cerro Prieto geothermal area in Mexico. Since 1973, the Cerro Prieto geothermal fields have supplied electricity to most of the state of Baja California, including the city of Mexicali, as well as supplying some power to southern California. It is the largest known water-dominated geothermal field in the world and, with 720-megawatts of generating capacity, it is the second largest geothermal power plant on Earth. However, it also produces tons of silica brine in its evaporation ponds, for which there has yet to have been found a use. The basin of nearby Laguna Salada is also a trough, or graben, in this case formed by the Laguna Salada Fault on the east and the Sierra Juárez Fault on the west. Both the Salton Trough and Laguna Salada have surface basins that are below sea level today.

ENDNOTE 6. Bahía Concepción is one of the best examples of a mini-extensional basin in the Gulf. It formed along the Baja California Peninsula during the opening of the Gulf, and the bay's long and narrow shape results from a graben (a half-graben, actually) created by northwest-southeast trending faults, the eastern one lying on the Peninsula Concepción. With a length of 25 mi (40 km) and an area of 100 sq mi (270 sq km), Bahía Concepción is one of the largest fault-bounded bays in the Gulf. Around the bay are Oligocene to Miocene igneous rocks—andesites, basalts, tuffs, and breccias. There are also two areas on Peninsula Concepción where Cretaceous (75 mya) granodiorite outcrops. The shallow bay, mostly 80–100 ft (25–30 m) depth, was probably a non-marine basin during most of the Pleistocene, when sea levels were much lower.

Bahía Concepción, Baja California Sur

ENDNOTE 7. Zoologists purporting to document trans-peninsular seaways across the Baja California Peninsula often cite Smith (1991) as a source of historical geology for the region (e.g., Blair et al. 2009; Lindell et al. 2005, 2008). However, Judith Terry Smith is a paleontologist, not a hard-rock geologist, and her 1991 paper was a summary of fossil marine molluscs from northwestern Mexico, from which she drew inferences of past coastal seaways and embayments. The Oligocene to Pliocene faunas she described were clearly explained as coastal embayments on mainland Mexico, before the Baja Peninsula separated and the Gulf of California was established. Among the marine basins described in Smith (1991) are a Middle Miocene marine invasion into the area north of present-day Cabo San Lucas (the "Cabo Trough"), a late-middle Miocene (13 Ma) extension of the Pacific to the present-day location of Tiburón Island, and a late Miocene (6 MYA) seaway as far north as the Salton Trough (e.g., the Imperial Formation of San Gorgonio Pass, California). All of these occurred before the Baja California Peninsula separated from mainland Mexico and the modern Gulf formed. Smith sometimes, confusingly, referred to these marine basins using the term "early Gulf." However, she clearly stated that the actual opening of the Gulf of California took place 6 MYA, well after her documented "early Gulf" embayments. In describing these embayments and their molluscan faunas, Smith stated, "From the late Oligocene to late Miocene (30-6 Ma), the Baja California Peninsula was contiguous with mainland Mexico; Cape San Lucas was adjacent to Punta Mita and the area north of Cabo

Corrientes." Unfortunately, it seems that many zoologists simply have not carefully read Smith's descriptions of these pre-Gulf seaways and basins. The fault lies party with Smith herself, because she occasionally referred to these pre-Gulf embayments as the "Gulf of California" or the "Ancient Gulf," meaning, one must presume, that she choose to give these temporary embayments the same name as the modern Gulf—clearly confusing readers.

ENDNOTE 8. The Colorado Plateau extends across western Colorado and New Mexico, and eastern Utah and Arizona. During the late Cretaceous, the region was below sea level and covered by extensive marine sediments deposited in the great Western Interior Seaway. In fact, much of the continent in this region was under the sea for most of the last 480 million years, until the final retreat of the great "Cretaceous Seaway" in the early Cenozoic, ~60 mya. The uplift of the plateau may have begun ~25 mya and continues today. The amount of uplift has been estimated at 1150–7220 ft (350–2200 m), depending on location. The source mechanism of the uplift is still unclear, but hypotheses include influence of a mantle plume, lithospheric thinning and/or delamination, and subduction of the Farallon Plate margin.

ENDNOTE 9. The largest and longest-lived of the known freshwater lakes that filled the Salton Trough's Imperial Valley was Lake Cahuilla (also known as Lake Leconte). Lake Cahuilla was the last lake to fill the valley before the man-made creation of the Salton Sea in 1905, and it covered over 2000 sq mi (5180 sq km) to a depth of more than 300 ft. It was almost 100 miles long by 35 miles wide, extending from the delta region in Mexico, north almost to Indio, California (six times the size of the Salton Sea). The ancient shoreline of Lake Cahuilla is visible as a band of travertine deposits ~40 feet above mean sea level throughout the region. Travertine (or "tufa") is a freshwater calcium carbonate deposit created by algae living along shallow lakeshores or, occasionally, at geothermal springs. The time of Lake Cahuilla's origin is unknown, but we do know it was present before the year 1200 A.D. and was gone by the time Spanish explorers entered the region in the late 16th century. Evidence clearly indicates that the early Cahuilla Indians used the resources of the lake. Evidence suggests that freshwater lakes existed intermittently in the Salton Trough during the Holocene. The lakes formed whenever the Colorado River flowed west into the trough instead of south to the Gulf of California. Stratigraphic records, radiocarbon dates, and archeological data suggest these lakes filled to a maximum of 12 m above sea level.

ENDNOTE 10. Due to excessive damming of the Colorado River, beginning with construction of Hoover Dam in 1936, and multiple water diversions, almost none of the Colorado River flow reaches the Gulf of California today except in extremely wet years when heavy snows have fallen in the Rockies. The salinity of the upper Gulf has significantly increased as river flow has decreased. Before the damming began, the Colorado River delivered an annual average of ~565 billion $ft^3$ (16 billion $m^3$ ) of fresh water and 160 million metric tons of sediment to the upper Gulf. Today, the delta is no longer building and instead is being slowly washed away by tides and currents. The main source of new sediment carried to the Gulf today are the rivers of southern Sinaloa and Nayarit. Seven western U.S. states, along with Mexico, have legally been allocated a total water volume that exceeds typical flows in the Colorado River. A total of 325 billion $ft^3$ (9.2 billion $m^3$) is allotted to the Upper Basin states (Colorado, Wyoming, Utah, New Mexico) and the same amount to the Lower Basin states (California, Arizona, Nevada). Mexico is entitled to 63.5 billion $ft^3$ (1.8 billion $m^3$) of water per year, but almost never receives that volume, and what does cross the border is too polluted for most purposes. In Arizona and California, ~70 percent of the allotment is diverted for agriculture. Current U.S. agricultural water prices for Colorado River water range from $16 to $32 per acre-foot, whereas municipal prices range from $300 to more than $880 per acre-foot. A brief reflection on these statistics illuminates the myriad conflicts that revolve around water usage and conservation in the Southwest today.

ENDNOTE 11. Much the same terrestrial riparian animal community is recorded from the San Pedro River Valley of southern Arizona. Here, 6 million years of biotic changes are recorded in one of the best-known late Cenozoic sequences of terrestrial life in North America, along with one of the most notable records of the first Americans and extinct mammals known on the continent.

ENDNOTE 12. During dispersal by winds (or water), dune sands get well sorted, resulting in sand grains being relatively uniform in size at any given place within a dune. Most dunes show a low-angle windward side called the “stross slope” and a high-angle slip face called the “lee slope.” The ramp angle on a stross slope might be 10º to 15º, whereas the lee slope generally is near 33º, the angle at which gravity overcomes the adhesion of the sand grains and the sand begins moving down slope (known as the “angle of repose”). Windblown sand moves up the gentle stross slope by “saltation” until it reaches the dune crest, where it collects. The uppermost lee slope is destabilized when too much sand accumulates and gravity pulls material down the slip face in a small-scale avalanche. The most common dune types in the Gran Desierto are barchans and star dunes. Barchans (derived from a Turkish word) are crescent-shaped dunes that build where wind direction is largely from one direction. Star dunes are multiarmed, pyramid-shaped dunes typical of areas with changing wind direction; building up more than out, they can rise to hundreds of feet.

ENDNOTE 13. Eolian sediments are those derived through the action of winds. The term “eolian” (or “aeolian”) derives from Greek mythology, and relates to *aeolus*, a literary term referring to the sighing or moaning sound produced by the wind. Five categories of eolian dunes have been identified in the Gran Desierto, reflecting historic climatic and sea-level conditions that occurred during and following the Last Glacial Maximum 20,000 years ago. These dune categories are: (1) late Pleistocene relict linear dunes, (2) degraded crescentric dunes that formed ~12,000 years ago, (3) early Holocene western crescentric dunes, (4) eastern crescentric dunes that formed ~7,000 years ago, and (5) gigantic star dunes formed by alternating/opposing winds over the last 3,000 years—some exceeding 330 ft (100 m) in height. South of the Gran Desierto's active dune fields are stabilized and unstabilized coastal eolian dunes that extend all the way to Puerto Lobos (Cabo Tepoca), Sonora.

ENDNOTE 14. The long, narrow shape of the Gulf of California creates a "bathtub effect" for its waters. The tidal range is very small at the center "nodal point," and increases northward and southward from the center like water sloshing back and forth in a tub. The tidal range (amplitude) is greatest in the very narrow, shallow northern Gulf where water from each tidal flow "piles up" higher, like in a fjord. The tidal range at the very head of the Gulf is nearly 33 ft (10 m).

ENDNOTE 15. In contrast to the Gulf coast, many of the mountains of the western (Pacific) coast of the Baja California Peninsula, including the mountains of Cedros Island, the Vizcaino Peninsula, and the Magdalena Bay islands, represent scrapings from the seafloor of the Pacific Plate and contain serpentine mantle rocks that had been deeply buried, metamorphosed, and brought back to the surface. In contrast, the Volcanic Tablelands, seen in the broad plateaus and mesas of southern Baja California are composed of much younger rocks formed by volcanism associated with the passing of the East Pacific Rise under the continent and the beginning of the opening of the Gulf. Some of the oldest exposed rocks in North America can be found in northwest Sonora/southwest Arizona, between the Cabeza Prieta National Wildlife Refuge/Pinacate Mountains and Caborca (Sonora). These exposures of ancient Paleoproterozoic basement rocks (diorites and granites) have uranium-lead (U-Pb) zircon ages of 1.6 to 1.7 billion years. The Cabeza Prieta/Pinacate exposures are located along the truncated southwestern margin of the ancient continent of Laurentia (now recognized as the North American Craton), and some researchers have noted their geochemical similarity to basement rocks in northeastern Australia, suggesting ties from the time of the ancient supercontinent of Rodinia. Sitting on the southwestern edge of the great Laurentian Craton, these ancient rocks record a geological history that predates the breakup of Rodinia ~750 mya.

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## GLOSSARY OF COMMON GEOLOGICAL TERMS

**absolute dating**. A method of geological dating employing isotope decay that gives a direct measure of the amount of time that has elapsed since formation of rocks or other objects. For example, $C^{14}$ is typically used to date fairly recent events (e.g., biological materials), K/Ar used to date igneous rocks of volcanic origin (K decays to Ar, a gas), and uranium isotopes are used to date events that occurred many millions of years ago ($U^{237}$ and $U^{235}$ have half-lives of 4.7 X $10^9$ and 0.7 X $10^9$ years, respectively).

**accrete** (verb). In geology, the term for the addition of terranes (small land masses or pieces of crust) to another, usually larger, land mass.

**alkaline**. Term pertaining to a highly basic, as opposed to acidic, substance (e.g., hydroxide or carbonate of sodium or potassium).

**allochthonous**. In geology, referring to something formed elsewhere than its present location (e.g. **autochthonous terranes,** sometimes called "exotic" terranes).

**alluvial fan**. A fan-shaped deposit of sand, mud, etc. formed by a stream where its velocity has slowed, such as at the mouth of a ravine or at the base of a mountain.

**alluvium** (noun). A deposit of sand, mud, etc., formed by flowing water. (alluvial - adj.)

**alluvial soils**. Loose soils eroded from a slope and deposited by running water.

**andesite.** A volcanic rock with about 52-63 percent silica ($SiO_2$). Especially common in volcanic arcs (i.e., subduction zones near the edge of continents).

**anticline**. In geology, a ridge-shaped fold of stratified rock in which the strata slope downward from the crest. Cf. **syncline**.

**aquifer**. A subsurface rock or sediment that is porous and permeable enough to store water (e.g., sandstone).

**Archaeobacteria**. A group of microorganisms, including the methanogens and certain halophiles and thermoacidophiles, that have RNA sequences, coenzymes, and a cell wall composition that are different from all other organisms; considered to be an ancient form of life that evolved separately from the bacteria and blue-green algae (Cyanobacteria) and sometimes classified as one of the kingdoms of life.

**argillite**. Massive fine-grained metamorphic rock that is equivalent to siltstone.

**arroyos**. Stream beds that are usually without surface water except during rains (primarily a southwestern U.S/northwestern Mexico term).

**ash** (geology). Very fine-grained and unconsolidated volcanic "dust" composed of broken particles of volcanic glass, crystals, and rock fragments.

**ash flow**. A dense cloud composed dominantly of hot ash and pumice. Can produce an ash-flow deposit (tuff); a type of pyroclastic flow.

**bajada**. An "apron" of land across the front of a mountain range created from multiple, usually overlapping alluvial deposits over time; the outwash plains of desert mountain ranges. *Cf.* **pediment**.

**basalt**. A dark-colored, fine-grained, iron-rich volcanic rock with less than 52 percent silica ($SiO_2$). One of the most common volcanic rocks on Earth, underlying most ocean basins as well as large areas of the continents. Basalt is produced by melting of mantle rocks, and eruption of basalt is widely viewed as a principal means of transporting mass and heat from the mantle to the crust.

**basement/basement rock**. (1) The crust of the Earth beneath sedimentary deposits, usually consisting of metamorphic and/or igneous rocks of Precambrian age. (2) The oldest rocks in a given area; a complex of metamorphic and igneous rocks that usually underlies sedimentary deposits; typically Precambrian or Paleozoic in age.

**basin**. Any large depression on the Earth's surface in which sediments are deposited.

**Basin-and-Range Province**. One of the world's most extensive systems of fault-bounded mountains separated by sediment-filled valleys, extending across Idaho, Oregon, Nevada, Utah, Arizona, New Mexico, California, and northern Mexico. Roughly corresponding to the arid region of North America. Mostly produced during the last 25 million years, due to extension of the Earth's crust after subduction ceased to the west. High-angle faults are typically found along margins of the mountain ranges; the relative uplift of the mountain ranges and subsidence of the valley basins took place along these faults, many of which are still active today.

**batholith**. A large region of plutonic rocks, such as the granite batholith of the Sierra Nevada in California. Most batholiths consist of many bodies of magma that were intruded over an extended period of time. Some geologists define "batholith" as a body of plutonic rock greater than 40 $mi^2$ in size.

**beachrock**. Sedimentary rock formed along tropical shorelines by precipitation of calcium carbonate out of seawater and the cementing together of sand grains and shells. Notable North American examples occur in Florida and the northern Gulf of California. It is thought that beachrock forms where sea water is supersaturated with calcium carbonate and there is intense evaporation on a shoreline.

**bedrock**. The general term referring to the rock underlying other unconsolidated material and/or soil.

**benthic**. Pertaining to a sea bed, river bed, or lake floor. Used of organisms inhabiting these areas. Related terms include **epibenthic** (living on the surface of the bottom substratum) and **infauna** (animals living just beneath the surface of the seafloor, within the sediment or sand).

**biostratigraphy**. The study of rock layers (e.g., distribution, environment of deposition, age) based on their fossils. (biostratigraphic – adjective).

**biota**. The living species and individuals of an area, including plants, animals, protists, fungi, etc.

**biotic**. Relating to life or living organisms.

**brackish water**. Naturally-occurring water that is salty, but less salty than seawater.

**breccia**. A sedimentary or volcanic rock composed of angular rock fragments set in a finer-grained matrix.

**calcite**. A common crystalline form of natural calcium carbonate, $CaCO_3$, that is the basic constituent of many protist and animal skeletons, as well as limestone, marble, and chalk. Also called calcspar.

**calcareous**. Composed largely of calcium carbonate.

**caldera**. A large circular volcanic depression, larger than a “crater,” and usually originating due to collapse of the roof of a magma chamber.

**caliche**. A hard calcium carbonate deposit usually just above the water table, formed as calcium-rich groundwater is drawn upward by capillary action; evaporites.

**carbon-14 dating**. Method for radiocarbon dating to determine the age of an organic substance by measuring the amount of the carbon isotope, carbon-14, remaining in the substance; useful for determining ages in the range of 500 to 70,000 years.

**carbonate**. A mineral composed mainly of calcium (Ca) and carbonate ($CO_3$) ions, but which may also include magnesium, iron and others. Rock or sediments derived from debris of organic materials composed mainly of calcium and carbonate (e.g., shells, corals, etc.), or from the inorganic precipitation of calcium (and other ions) and carbonate from solution as in seawater. Carbonate rocks include limestone, dolomite, chalk, and others.

**carbonate platform**. A broad (100s of meters), flat, shallow submarine expanse of carbonate rock, more common in the early-middle Paleozoic.

**carbonate bank**. A narrow (tens of meters), fairly flat, shallow, submarine plateau of carbonate rock, more common from the middle-late Paleozoic to the present (e.g., the Bahamas Banks).

**chalk**. A soft compact calcite, $CaCO_3$, with varying amounts of silica, quartz, feldspar, or other mineral impurities, generally gray-white or yellow-white and derived chiefly from fossil seashells.

**climate**. A statistical summation of weather over an extended period of time.

**continental crust**. The Earth's crust that includes both the continents and the **continental shelves**.

**continental shelf**. The part of the continental margin from the coastal shore to the continental slope; usually extending to a depth of about 200 meters and with a very slight slope (roughly 0.1 degrees).

**cordillera.** A long and extensive system of mountain ranges, often in somewhat nearly parallel chains, especially the principal mountain system of a continent.

**cordilleran gap.** A low spot, or break in a cordillera, such as the North American Cordilleran Gap between the Rocky Mountains/Colorado Plateau and the Sierra Madre Occidental of Mexico (where the Madrean Sky Islands occur).

**core (of the Earth)**. The innermost portion of the interior of the Earth, lying beneath the **mantle** and extending all of the way to the center of the Earth. The Earth's core is very dense, rich in iron, and the primary source of the planet’s magnetic field.

**cross-bedding**. The arrangement of successive sedimentary beds at different angles to each other, indicating that the beds were deposited by flowing wind or water.

**coquina**. Conglomerates formed from shells.

**cross bedding**. Beds deposited at an angle to other beds.

**crust (of the Earth).** The outermost layer of the Earth (above the **mantle**) varying in thickness from about 10 kilometers (6 miles) below the oceans, to 65 kilometers (about 40 miles) below the continents; represents less than 1 percent of the Earth's volume.

**dacite**. An extrusive volcanic rock resembling andesite but containing free quartz.

**deflation**. The removal of material from a surface by wind.

**delta**. Sediments deposited in the ocean at the end of a river.

**deposition** (geology). Any accumulation of material, by mechanical settling from water or air, chemical precipitation, evaporation from solution, etc.

**desert**. An arid biome in which water loss due to evaporation and transpiration by plants exceeds precipitation. This is Earth's driest biome, with vegetation limited by the extreme aridity.

**detritus**. Geology: fragments of material which have been removed from their source by erosion. Biology: small particles of organic material, often dead plants or animals and/or fecal matter

**diagenesis**. All of the changes that occur to sediments, and also to a fossils, after initial burial; includes changes that result from chemical, physical as well as biological processes. The study of diagenesis is part of the discipline of **taphonomy**.

**diatom**. Very small, photosynthetic protists with siliceous skeletons; members of the phylum Stramenopila (or, Bacillariophyta).

**diatomite**. Diatomite, or **diatomaceous earth**, is a siliceous sedimentary rock formed from the accumulation of **diatoms** and similar **plankton**.

**dike**. An intrusion of igneous rock cutting across existing strata; igneous material filling a crack or joint in rocks.

**dip**. Angle of inclination of layers or faults.

**drag folding**. Drag folding is one of several types of rock folding. Folding normally occurs in conjunction with faults, and it represents the bending of rock before it breaks. Normally, folding occurs when the rocks are deeply buried. Drag-folded rocks are folded due to one rock layer being "pulled" by another.

**East Pacific Rise/Ridge.** A major oceanic crustal spreading center and a submarine volcanic chain. The spreading center itself is a valley between two ridges, on the west side is the Pacific Plate, and on the east side is the North American Plate and a number of other, smaller plates (Riviera, Cocos, Nazca, and Antarctic Plates). The spreading rate is ~70 mm/yr on each side of the spreading center. Oceanic crustal plates ride on the underlying mantle as it moves like a conveyor belt away from spreading centers and toward subduction zones.

**emergence** (Geology). Area once under water that has been raised above the water surface.

**eolian**. Relating to, or arising from the action of wind.

**escarpment**. A steep cliff, either on land or on the sea floor; often, though not always along a fault.

***estero.*** Commonly used word in Mexico for tidally-flushed, hypersaline coastal seawater lagoons. Also known as "negative estuaries."

**estuary** (noun). An area where fresh water comes into contact with seawater, usually in a partly enclosed coastal body of water. Also known as a "positive estuary."

**estuarine** (adjective). Referring to something existing in, or associated with an estuary.

**evaporite**. A deposit of salt minerals (e.g., halite, gypsum, anhydrite) left behind by the evaporation of sea water or fresh water high in minerals (especially salts); usually forming within a restricted basin.

**exotic terrane** (see allochthonous terrane).

**extrusive rock**. Igneous rock that originates as molten material emerging on the Earth's surface and then solidifying. *Cf*. **intrusive**.

**extensional trough**. A trough (elongated depression on the Earth's surface) caused by extension and subsequent subsidence of the crust.

**fault, fault line**. A fracture in rocks along which vertical or horizontal movement occurs.

**fault scarp**. Uplifted cliff or bank along a fault line.

**feldspar**. An abundant rock-forming mineral typically occurring as colorless or pale-colored crystals and consisting of aluminosilicates of potassium, sodium, and calcium.

**flocculation**. The process of forming small clumps or masses, usually by precipitation out of suspension.

**flocculant**. A substance causing flocculation, or the clumping of particles in suspension.

**fluvial**. Sediments deposited by stream action.

**foraminiferan**. A member of the protist phylum Granuloreticulosa. Most frequently found in marine and brackish waters and characterized by the presence of a skeleton, or test, with one to multiple chambers and long, thin pseudopods that branch and anastomose. Much of the world's chalk, limestone, and marble is composed largely of foraminiferan tests or the residual calcareous material derived from the tests. Informal: **foram**.

**formation (geology)**. The fundamental unit of stratigraphic classification, consisting of rock layers that have common characteristics allowing them to be distinguished from other rocks and to be mapped as separate bodies. Formations are typically named for geographic places.

**forearc**. A depression in the seafloor located between a subduction zone and an associated volcanic arc. Typically with a steep inner trench wall that flattens into the upper trench slope, also known as the **forearc basin**.

**fossiliferous**. Containing fossils.

**gabbro**. A dark-colored, coarse-grained, iron-rich plutonic rock.

**geosyncline**. A syncline on a continental scale.

**graben**. An elongated down-dropped block of the Earth's crust lying between two faults (displaced downward relative to the blocks on either side), e.g., a rift valley. *Cf.* **horst**.

**granite**. An intrusive, high-silica, coarse-grained plutonic rock (typically with more than 70 percent silica – $SiO_2$) composed mainly of coarse-grained crystals of quartz and feldspar. Granite is the compositional equivalent of the volcanic extrusive rock rhyolite, but it cooled slowly at depth so all of the magma crystallized and no volcanic glass remained.

**granodiorite**. A coarse-grained, intrusive, plutonic rock containing quartz and plagioclase, between granite and diorite in composition.

**Gulf Extensional Province**. Most authors restrict this province to the Gulf of California and easternmost coastline of Baja, plus the Salton Trough. However, some researchers (e.g., Stock & Hodges 1989) have included the broad coastal plains of Sonora-Sinaloa-Nayarit in the province.

**halophilic.** "Loving salt"; an adjective applied to plants and animals that have evolved to live in saline environments.

**halophyte**. Salt-tolerant plants that grow in salty or alkaline soils or habitats, such as estuaries and esteros.

**horst**. An uplifted block of Earth's crust bounded by faults. *Cf.* **graben.**

**hydric** (ecology). A habitat or environment with a high amount of moisture; very wet. *Cf.* **mesic, xeric**.

**hydrothermal vent**. A place on the seafloor, generally associated with spreading centers, where warm to super-hot, mineral-rich water is released; typically supports a diverse community of living organisms.

**ichnology** . The study of trace fossils.

**igneous rocks**. Rocks formed by cooling of molten material. Any rock solidified from molten or partly molten material (magma), including rocks crystallized from cooling magma at depth (intrusive) and those poured out onto the Earth's surface as lavas (extrusive).

**index bed**. Also known as key bed, key horizon, and marker bed. A stratum or body of strata that has distinctive characteristics so that it can be easily identified. A bed whose top or bottom is employed as a datum in the drawing of structure contour maps.

**indicator species**. A plant or animal which is restricted to, and thus indicates, a specific environment.

**intertidal zone**. The area of the shoreline between the highest high tides and lowest low tides, alternately covered by sea water and exposed to air.

**Intrusive rocks**. The process by which magma is emplaced into other rocks. Intrusive rocks are igneous rocks that have solidified from molten material (magma) within the Earth's crust that has not reached the surface. All bodies of granite are intrusions. *Cf.* **extrusive**.

**island arc**. A curved (arc-shaped) linear chain of volcanic islands that rise from the seafloor and overlie subduction zones, usually near a continent. The convex side usually faces the open ocean, while the concave side usually faces the continent, e.g., the Aleutian Islands in Alaska. Where such volcanic belts occur within a continental mass overlying a subduction zone, the term **volcanic arc** is used.

**isotopic age**. Estimated age determined by radiometric dating.

**joint**. A fracture in a rock mass that is not associated with movement.

**K/AR.** Potassium-Argon ratio. The isotope Potassium 40 decays to Argon 40 at a predictable rate, so the ratio of these two elements can be used to date rocks (since their time of origin).

**karst**. A type of topography formed by dissolution of rocks like limestone and gypsum that is characterized by sinkholes, caves, and subterranean passages.

**lacustrine**. Of, relating to, or associated with lakes (often used when referring to sediments in a lake).

**Laramide Orogeny**. A major period of mountain building in western North America, beginning ~75 mya and ending ~35-55 mya, and marked by widespread faulting and volcanism. The mountain building occurred in a series of pulses, with intervening quiescent phases. The event is usually ascribed to the submergence of the Farallon and Kula Plates (of the Pacific Ocean), which were sliding under the North American Plate.

**lateral fault (strike-slip fault).** A fault with a largely horizontal motion, with one side slipping past the other.

**limestone**. A bedded, carbonate, sedimentary deposit, usually formed from the calcified hard parts of microorganisms and composed of more than 50 percent calcium carbonate ($CaCO_3$).

**lithification**. The process by which sediment is converted to sedimentary rock.

**lithosphere**. The mostly rigid outer part of the Earth, comprising the crust and semi-viscous upper mantle above the asthenosphere of the mantle.

**littoral.** Very near shore; [restrictive] the intertidal zone.

**littoral zone**. The **intertidal zone**; also used in the less restrictive sense to include the shallow subtidal zone.

**loess**. A widespread, loose deposit consisting mainly of silt; most loess deposits formed during the Pleistocene as an accumulation of wind-blown dust carried from deserts, alluvial plains, or glacial deposits.

**Maar crater**. A crater formed by a violent explosion of subsurface magma meeting a water table (a phreatic explosion), without igneous (lava) extrusion; often occupied by a small circular rainwater-filled lake (except in very arid areas).

**magma**. Melted rocks below or within the Earth's crust (adj - magmatic). When magma explodes or oozes onto the surface of the Earth it is called lava. All extrusive igneous rocks form from cooling lava, and all intrusive igneous rocks form from cooling magma. The formation of magma is **magmatism**.

**mantle (of the Earth)**. In geology, that portion of the interior of the Earth that lies between the crust and the core.

**marine terrace**. A platform of ancient marine deposits (typically sand, silt, gravel) sloping gently seaward. Such platforms may be exposed along the coast, forming cliffs, due to uplift and/or the lowering of sea level (e.g., the marine terraces of coastal Southern California).

**marine transgression**. The movement of sea water onto land, to flood low-lying areas.

**maritime**. Living, or found in or near the sea; intimately connected to the sea in some way.

**marl (marlstone).** A lime/calcium carbonate-rich mudstone with variable amounts of clays and silts. The dominant carbonate mineral in most marls is calcite, but some contain aragonite, dolomite and siderite. Marl is commonly formed on lake bottoms or as marine deposits; it is particularly common in post-glacial lakebed sediments.

**mass extinction**. A highly elevated rate of extinction of many species, extending over an interval that is relatively short on a geological time scale.

**matrix**. The material around the grains or crystals in a rock.

**mesic** (ecology). A habitat or environment with a moderate amount of moisture. *Cf.* **hydric, xeric**.

**metamorphic core complex.** Surface exposures of metamorphic core rock (typically gneiss) and its associated batholithic rock (typically granite) created by displacement faulting.

**metamorphic rock**. Any rock derived from other precursor rocks by chemical, mineralogical and structural changes resulting from pressure, temperature or shearing stress.

**meteorite**. A non-orbital extraterrestrial body that enters the Earth's atmosphere. An estimated 1500 meteorites (100kg or larger) impact the Earth annually.

**methane**. $CH_4$.

**methanogens**. An organism that obtains energy by using carbon dioxide to oxidize hydrogen, producing methane as a waste product.

**midden**. A refuse heap piled by animals or humans; also, a dunghill or dungheap.

**monsoon**. A dramatic seasonal shift in winds that brings summer rains.

**moraine**. A mound or ridge of sediment gouged out and deposited by a glacier; **lateral moraine** (noun), deposited to the side of a glacier; **terminal moraine** (noun), deposited at the front of a glacier; **ground moraine** (noun), deposited on the land surface.

**nekton**. Aquatic organisms that are large enough, and mobile enough, to be able to maintain their position or distribution independent of the movement of water. *Cf.* **plankton**.

**nonconformity**. Sedimentary beds deposited on the eroded surface of igneous or metamorphic rocks.

**normal fault**. A simple fault caused by tension and gravity where the overhanging block slides downward; e.g, these are the main faults of horst and graben areas.

**North American Cordillera**. The nearly continuous mountain range running from Alaska to Southern Mexico, the only significant low gap being the Sky Island Region that separates the Rocky Mountains/Colorado Plateau from the Sierra Madre Occidental. Sometimes called the Western Cordillera or “the spine of the continent.”

**obsidian**. Black or dark volcanic glass that has conchoidal fracture. Valued by humans for use in making sharp-edged rock tools and projectile points.

**oceanic trench**. Deep, steep-sided depression in the ocean floor caused by the subduction of oceanic crust beneath either other oceanic crust or continental crust.

**organic**. Pertaining to any aspect of living matter; a term sometimes also applied to any chemical compound that contains carbon.

**orogeny**. The tectonic processes of folding, faulting, and uplifting of the Earth's crust that result in the formation of mountains.

**Pacific Coast Ranges**. Generally, the series of mountain ranges that stretches along the west coast of North America, west of the North American Cordillera, from Alaska to the California-Mexico border. The U.S.G.S. defines "Pacific Coast Ranges" as only those south from the Strait of Juan de Fuca in Washington to the California-Mexico border (e.g., excluding the Sierra Nevada and Cascade Ranges).

**Panamanian Seaway** (aka Panama Seaway). The open oceanic seaway between the Caribbean Sea/Atlantic Ocean and the Pacific Ocean that ultimately closed either around 15 or 2.6 million years ago by colliding tectonic plates. The closure of this seaway is thought to have initiated major changes in oceanic circulation and ocean-atmosphere temperatures, perhaps contributing significantly to increased Northern Hemisphere precipitation and glacial cycles that began 2.7-3.2 million years ago (if the younger closure date is correct).

**pediment.** The gently inclined erosional surface of bedrock that flanks the base of a mountain. Many pediments quickly grade into, or are covered with alluvium deposits from water runoff around the base of the mountain (especially in desert environments).

**pegmatite**. A coarse-grained dike, often with rare minerals such as beryl, tourmaline, or topaz.

**pelagic**. Pertaining to the water column of the sea or a lake. Used for organisms inhabiting the open waters of an ocean or lake. Pelagic organisms can be **planktonic** or **nektonic**.

**plagioclase**. A form of feldspar consisting of aluminosilicates of sodium and/or calcium; common in igneous rocks and typically white.

**plankton**. Aquatic organisms that are unable to maintain their position or distribution independent of the movement of water; drifters. *Cf.* **nekton**.

**playa, playa lake**. A desert area of interior drainage where water and fine sediments accumulate. Typically dry much of the year and filling during rainy seasons.

**plug**. An eroded neck of a volcano.

**pluton**. Any body of igneous rock that solidified below the Earth's surface (i.e., an intrusion). A pluton can be very small or very large, the latter being called batholiths. Batholiths can be more than 100 miles long and commonly consist of many individual plutons of different ages. Note: a narrow igneous body that forms when magma fills a fracture in a rock is called a dike. (adj. plutonic)

**plutonic.** Coarse-grained igneous rock that cooled and crystallized slowly beneath the Earth's surface.

**porphyry**. Igneous rock with larger crystals in a finer-grained matrix.

**Proto-Gulf Rift**. The subcoastal rift valley that formed along the west coast of North America, eventually filling with sea water (~5.5 mya) to become the modern Gulf of California.

**pumice**. A gas bubble-rich volcanic rock; typically with enough enclosed bubbles to allow it to float in water.

**pyroclastics**. Fragmented volcanic material produced (and usually ejected into the air) by a volcanic explosion or eruption.

**radiocarbon dating**. The determination of the age of an organic object from the relative proportions of the carbon isotopes carbon-12 and carbon-14 that it contains. The ratio between them changes as radioactive carbon-14 decays and is not replaced by exchange with the atmosphere.

**regression**. In geology, withdrawal of the sea from land, associated with a lowering of sea level.

**relative dating**. A method of geological dating in which only the relative age of a rock is determined and used, rather than the absolute age (e.g., using fossil indicator species to age a rock stratum). *Cf.* **absolute dating**.

**reverse fault, or thrust fault**. A fault in which the hanging wall block has been pushed up and over the footwall block (formed by compression).

**rhyolite**. An extruded volcanic rock or magma that contains more than about 70 percent silica ($SiO_2$). Rhyolite rock is usually light gray or white, but can be black if quenched to glass (obsidian), or red if high in iron. Granite is the slowly cooled and, consequently, coarse-grained plutonic equivalent of rhyolite.

**rift (geology)**. A long, narrow crack in the Earth's crust, which is bounded by normal faults on either side and forms as the crust is pushed apart by underlying magmatic activity.

**riparian area**. An area influenced by surface or subsurface water flows. Expressed (visually) biologically by facultative or obligate wetland plant species and hydric soils. **Hydroriparian**: a riparian area where vegetation is generally supported by perennial watercourses or springs. **Mesoriparian**: a riparian area where vegetation is generally supported by perennial or intermittent watercourses or shallow groundwater. **Xeroriparian**: a riparian area where vegetation is generally supported by an ephemeral watercourse.

**saltation.** Forward movement by hopping, skipping, or jumping; movement that is halting or episodic.

**salt marsh**. A coastal maritime habitat characterized by specialized plant communities, which occur primarily in the temperate regions of the world. However, typical salt marsh communities can also occur in association with mangrove swamps in the tropics and subtropics.

**schist**. A foliated metamorphic rock with visible aligned minerals, such as mica and amphibole.

**seafloor spreading**. The process of adding to the Earth's crust at mid-ocean ridges (rifts) as magma wells up and forces previously formed crust apart.

**sediment**. Any solid material that has settled out of a state of suspension in water or ice.

**sedimentary rock**. Any rock resulting from the consolidation of sediment over time.

**shear zone**. The zone between two different rock masses that are moving in different directions to one another due to a number of different processes.

**shield volcano**. A broad, domed volcano with gently sloping sides, characteristic of the eruption of fluid, basaltic lava.

**silica**. A hard, unreactive, colorless compound that occurs as the mineral quartz and as a principal constituent of sandstone and other rocks. Silicon dioxide, $SiO_2$. Adj. – siliceous

**sill**. A tabular intrusive body which is parallel to adjacent layering.

**sinkhole**. A natural depression in the surface of the land caused by the collapse of the roof of a cavern or subterranean passage, generally occurring in limestone regions (e.g., *cenotes*).

**sky islands**. High mountain ranges isolated from each other by intervening basins of desert and grassland or other disparate ecosystems that are barriers to the free movement of woodland and forest species from one "island" to another, in much the same way seas isolate species on oceanic islands. In the American Southwest, sky islands are usually defined as isolated mountains in the Cordilleran Gap that are high enough to have oak woodland and are not connected to the North American Cordillera itself. About 65 of these ranges occur in southeastern Arizona/southwestern New Mexico/northwestern Mexico, and they act as biological "stepping stones" between the Rocky Mountains and the Sierra Madre Occidental.

**speciation**. The evolution of a new species.

**spreading center/spreading ridges**. A place where two lithospheric plates are being created, separating, and moving away from one another. *cf.* **East Pacific Rise**

**strata**. Recognizable layers of rock that were deposited at different times (generally sedimentary). *cf.* **stratigraphic, stratigraphy**

**stratigraphic**. Pertaining to the description of rock strata.

**stratigraphy**. The scientific study of rock strata.

**strike**. In geology, the direction or trend of a bedding plane or fault, as it intersects the horizontal.

**strike-slip fault.** A fault or planar surface along which adjacent blocks of the Earth's crust slide horizontally past one another; faults with lateral movement. Contrasts with a dip-slip fault along which motion is dominantly vertical. A strike-slip fault occurring at the boundary between two plates of the Earth's crust is a **transform fault**.

**subduction** (verb, **subduct**). The process by which oceanic crust is destroyed by sinking into the mantle along an inclined subduction zone. A subduction zone is a long narrow area in which subduction is taking place. Subduction zones are typically where one lithospheric plate dives beneath another, e.g., the Peru-Chile trench, where the Pacific Plate is being subducted under the South American Plate.

**subtidal**. The shallow (continental shelf) region below the intertidal zone (unlike the intertidal zone, the subtidal zone is never exposed to air).

**syncline**. A fold of rock layers that is convex downwards; a downfold or basin where beds drop towards each other. *Cf.* **anticline**.

**tableland**.  A wide, level, elevated expanse of land; a plateau.

**taphonomy**.  The study of what happens to a fossil from the time of its initial creation (e.g., the death of an organism or the imprint left by the movement of an organism) and the time that the fossil is discovered by a paleontologist.  For example, shells or bones can be moved my running water, and later be compressed by overlying sediment.

**tectonic**.  Large-scale geological processes in, or relating to, the Earth's crust.

**tectonic plates**.  Large pieces of the Earth's lithosphere (crust + upper mantle) that are separated from one another by discreet boundaries.  Plate boundaries may be convergent (collisional), divergent (spreading centers), or transform boundaries.  There are 8 major (and many minor) plates moving about the surface of the Earth.  Oceanic crustal plates ride on the underlying mantle like a conveyor belt as they slowly move from spreading centers (spreading ridges) to subduction zones.

**tephra.**  A collective term for volcanic ejecta.  Fragmental material produced by a volcanic eruption (regardless of composition or size).  Airborne fragments are typically called pyroclasts.  Pyroclasts that have fallen to the ground remain as tephra unless hot enough to fuse together into pyroclastic rock or tuff.

**terrain**.  A general term used to refer to a piece of the crust that is usually smaller than a continent but larger than an island.  A tract of land with distinctive physiographic features.

**terrane**.  In geology, a fault-bounded area with a distinctive structure and geological history.  Or, any rock formation or series of formations or the area in which a particular formation or group of rocks is predominant.  *Cf.* **exotic terrane**

**test**.  In biology, a hard outer shell or casing of a living organism that functions as a skeleton.

***tinaja***.  A term used in the Southwest for a pool formed in a rock depression carved over time by episodic moving water.  Tinajas often hold water, from rain or temporary streams, through long dry periods and are thus important sources of moisture for animals and plants.

**tombolo**.  A strip of sand or mud or rocks, deposited by waves or currents, connecting an island or headland to the mainland.

**trace fossil**.  Evidence left by organisms, such as burrows, imprints, coprolites, or footprints. Trace fossils are not preserved parts of the organism.

**transform boundary**.  = transform fault

**transform fault**.  A type of fault whose relative motion is predominantly horizontal in either a right or left direction.  These faults end abruptly and are connected on both ends to other faults, ridges, or subduction zones.  Most transform faults are hidden in the deep oceans where they form a series of short zigzags accommodating seafloor spreading.  These are the only type of strike-slip faults that can be classified as plate boundary.  Transform faults neither create nor destroy crust (i.e., they are conservative plate boundaries).

**transgression**.  A rise in sea level relative to the land, resulting in seawater flooding onto land.

**travertine**.  Banded calcite formed in hot-spring deposits (the rock form is known as **onyx**).

**trough**.  A long depression in the Earth's crust.

**tuff**.  A general term for consolidated rocks made of material ejected from volcanic explosions (e.g., consolidated yellow or orange ash is a common form of tuff). Sometimes when ash and pumice fall from the air they are still so hot that they fuse together, creating a rock called “welded tuff.” Most of the unusual rock formations (“hoodoos”) at Chiricahua National Monument in Arizona are eroded welded tuff.

**tufa**. A variety of limestone formed by the precipitation of carbonate minerals from ambient temperature water bodies (as opposed to travertine, which precipitates from geothermally heated springs). Tufa is sometimes referred to as meteogene travertine, in contrast to hot-spring, thermogene travertine. Tufa should not be confused with tuff, a porous volcanic rock.

**turbidity current**. A fast-flowing bottom current that moves down a slope, depositing suspended sediments over the floor of a body of water.

**turbidity flow**. A flow of dense, muddy water moving down a slope due to a turbidity current

**unconformity**. Any interruption of the continuity of a depositional sequence. A gap in the rock record usually represented by a period of erosion.

**uplift**. The process or result of raising a portion of the Earth’s crust via different tectonic mechanisms.

**vicariance**. The separation or fragmentation of a species' (or population's) range into two or more disjunct ranges among which little or no genetic continuity exists. The process of vicariance is presumed to lead to speciation event(s) (i.e., vicariance speciation).

**volcanic**. Describes the action or process of magma and gases rising to the crust and being extruded onto the surface and into the atmosphere; also applies to the resulting igneous rocks that cool on the surface of the Earth, including beneath water, which typically have small crystals due to the rapidity of cooling. *extrusive* - syn.; *plutonic* - ant.

**volcanic arc.** See **island arc.**

**water column**. The imaginary “column” of water in the sea (or in a lake) at any given location.

**water table**. The uppermost surface of natural groundwater, below which the subsurface material is saturated; the top of the groundwater aquifer.

**watershed**. An area of land where all of the surface and subsurface water drains to the same place; an area sharing a hydrolic system.

**weather**. The current state of the atmosphere in a given locality.

**Western Cordillera**. See North American Cordillera.

**xeric**. A habitat or environment with very little moisture, such as a desert. *Cf.* **mesic, hydric**.