A BRIEF GEOLOGIC HISTORY OF NORTHWESTERN MEXICO

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NOTE: This document is periodically updated as new information becomes available (see *date stamp* above). Photos by the author, unless otherwise indicated. This essay constitutes the draft of a chapter for the planned book, *A Natural History of the Sea of Cortez*, by R. Brusca; comments on this draft chapter are appreciated and can be sent to rbrusca@desertmuseum.org. References cited can be found in "A Bibliography for the Sea of Cortez" at www.rickbrusca.com.

SECTIONS

Pre-Gulf of California Tectonics and the Laramide Orogeny

The Gulf of California (herein, "the Gulf," Sea of Cortez) provides an excellent example of how ocean basins form. It is shallow, young (~7 Ma), and situated along a plate boundary (between the Pacific and North American Plates). It is also part of a large rift, dominated by right lateral (dextral) faults, that forms the San Andreas-Gulf of California fault system. The Gulf of California Rift, being an active oblique rift between the Pacific and North American Plates, probably initiated in middle Miocene time, 15-12.5 million years ago (Stock and Hodges 1989, Atwater and Severinghaus 1989, Lonsdale 1991, Atwater and Stock 1998).

However, the present-day topography of the Gulf and adjacent land masses (including the Baja California Peninsula) evolved through a series of great geological events that began many millions of years ago, long before the Baja California Peninsula and Gulf of California formed; geological events that stretch across all of western North America. This deep geological evolution was marked by two massive events—(1) tectonic plate submergence that led to an Andean-type subduction zone and its volcanic are, and (2) an immense extensional episode that culminated with the rupture of the Baja California Peninsula off of Mexico's west coast.

Beginning in the latest Paleozoic or early Mesozoic, the Farallon Plate began subducting under 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, or East Pacific Spreading Ridge (Endnote 1). To the west of the East Pacific Rise, the gigantic Pacific Plate was moving westward relative to the Farallon and North American Plates. The North American Plate was simultaneously moving slowly westward, driven by the opening of the Mid-Atlantic Ridge. As a result, the East Pacific Rise was slowly approaching North America, following along "behind" the Farallon Plate (see figure).

At first, the Farallon Plate's angle of subduction was fairly steep, about 45 degrees, which is typical of submerging plates. This deep dive engendered mountain-building uplift and volcanism along the western margin of North America due to compressional forces, crumpling its surface into mountains like a wrinkled rug being pushed from one edge. Evidence suggests that, for a time (perhaps ~70-40 Ma), the subduction angle of the Farallon changed and the plate began moving under North America at a very shallow angle. During this shallow subduction phase ("flat-slab subduction"), the plate pushed nearly 1500 km (1000 miles) under North America before switching back to a steeper angle of subduction.

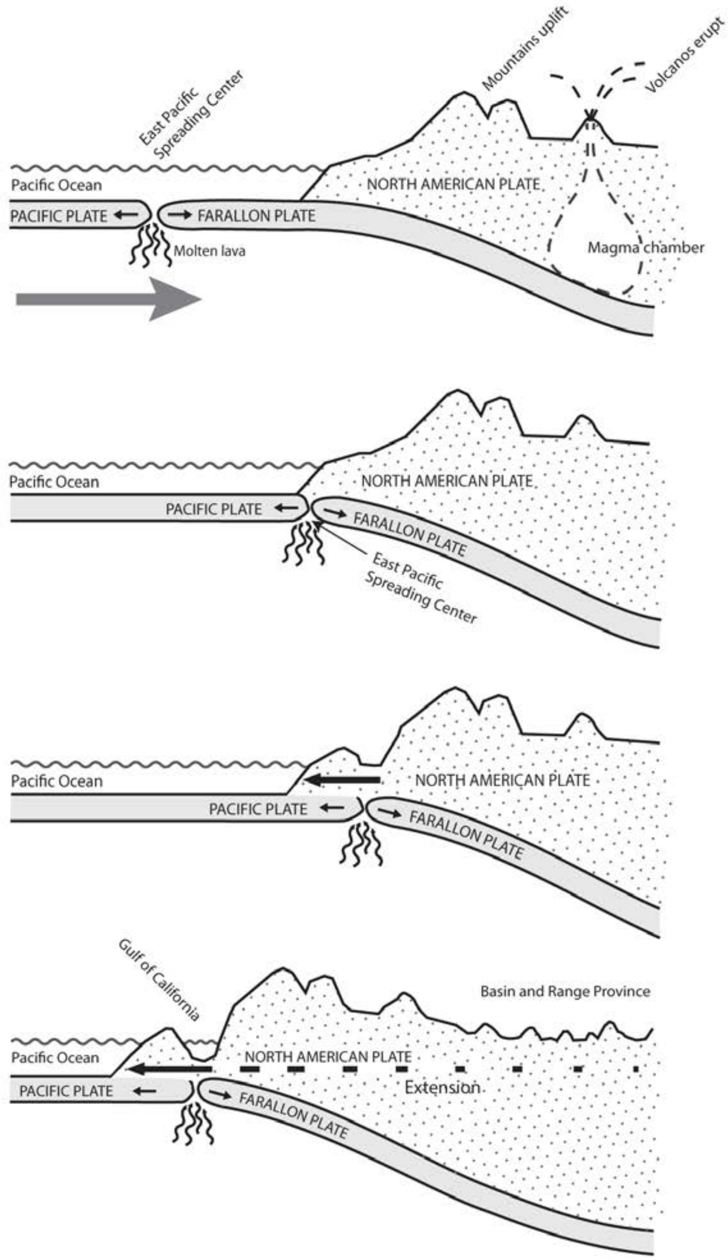
MOUNTAIN BUILDING IN THE SOUTHWEST

*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. **© Arizona-Sonora Desert Museum. Concept development by R. Brusca and W. Moore; graphic by Linda M. Brewer.**

Much of the initial uplift of the Rocky Mountains and Sierra Madre Occidental (of Mexico) took place during the subduction of the Farallon Plate. The Rockies formed mostly by compression and uplift; the Sierra Madre by uplift combined with a great deal of volcanic activity. Mountain building associated with the Farallon subduction may have taken place in a series of pulses and intervening quiescent periods. 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 included the Laramie Mountains of Wyoming (for which it was originally named).

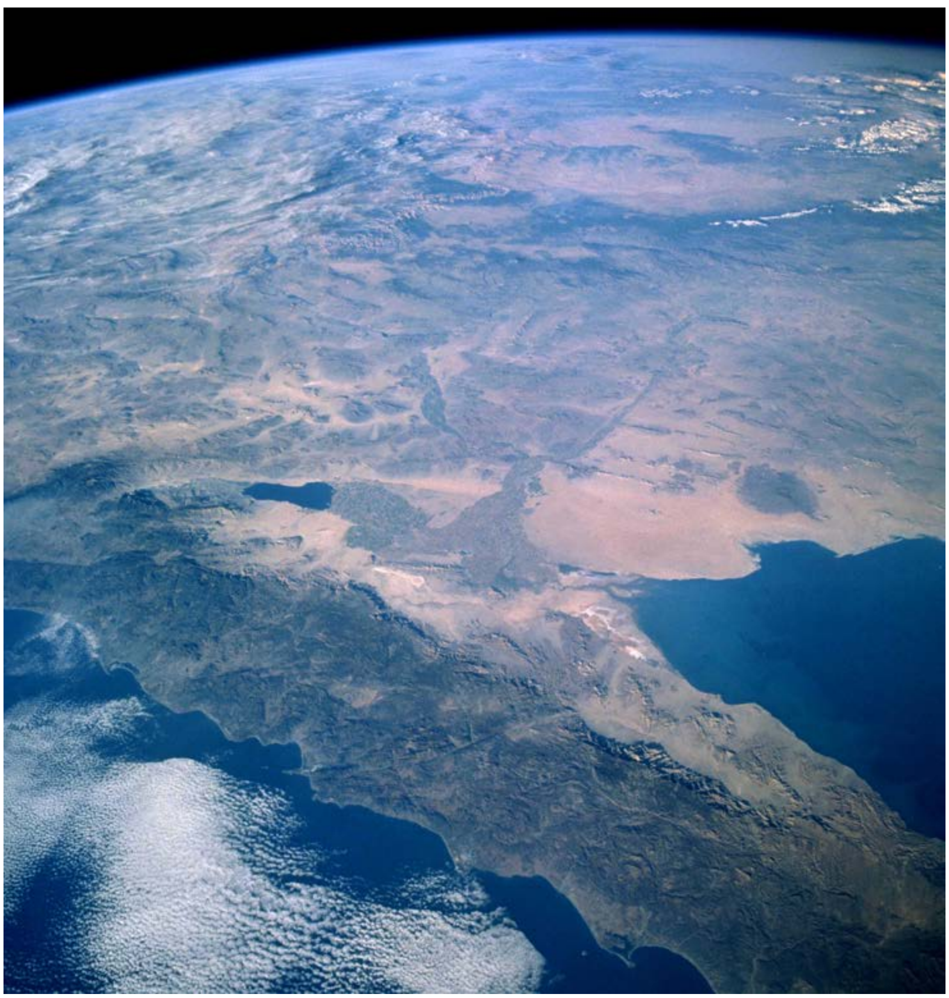
During that long period of subduction, the oceanic rocks of the Farallon Plate were carried deep enough to melt and turn to magma. Some of this magma crystallized below the surface to form intrusive batholiths (most commonly granitic in composition), including those that are now uplifted and exposed in the Sierra Nevada and Peninsular Ranges in California and along the length of the Baja California Peninsula.

Much of the melted rock, however, erupted at the surface as andesitic volcanoes, probably looking very much like present-day Mt. St. Helens in the Cascade Range. The Sierra Madre Occidental experienced massive and widespread volcanism. Today, the Rocky Mountains and Sierra Madre Occidental together comprise North America's Western Cordillera, a 4500 mile-long mountain chain. The only gap in this long chain of mountains is in southeastern Arizona/northeastern Sonora—the so-called Cordilleran Gap, studded by ~65 isolated ranges known as Sky Islands. (Endnote 2).

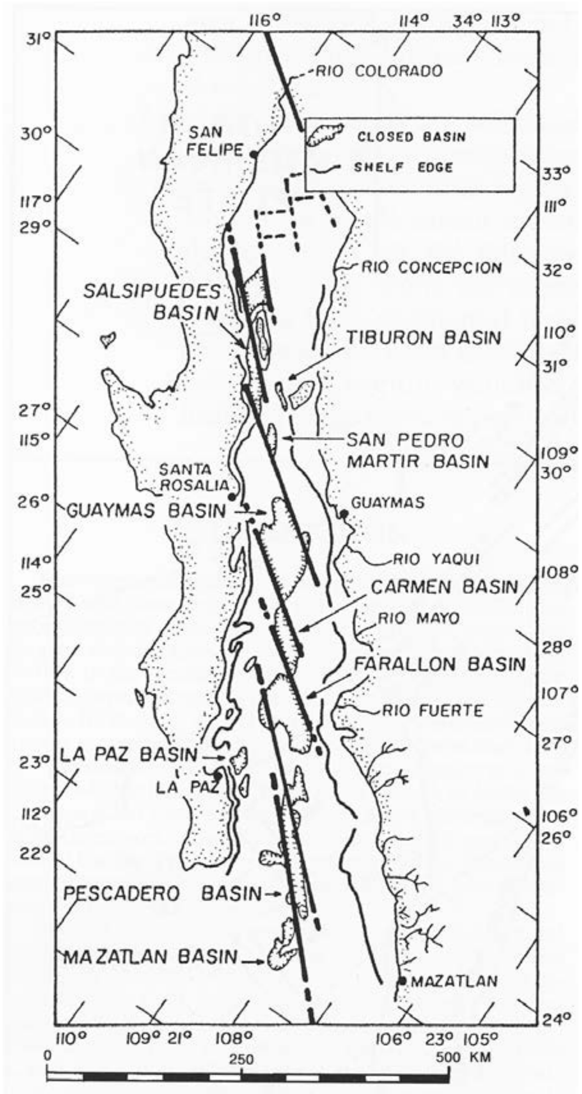
ERA	PERIOD		EPOCH	TIME (beginning)
Cenozoic	Quaternary		Holocene	10,000 ybp
			Pleistocene	2.6 mya
	Tertiary	Neogene	Pliocene	5.3 mya
			Miocene	23 mya
		Paleogene	Oligocene	33.9 mya
			Eocene	55.8 mya
			Paleocene	65.5 mya
Mesozoic	Cretaceous			145.5 mya
	Jurassic			201.6 mya
	Triassic			251 mya
Paleozoic	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)**

In addition to initiating the formation of igneous rocks by its subduction, the Farallon Plate and other smaller plates moving eastward in the Pacific Basin carried on their backs numerous volcanic oceanic islands and archipelagos, both submerged beneath the sea and emergent. When these oceanic islands and seamounts encountered the trench at America's continental margin, they were scraped off as the plates slowly dived beneath North America. These accreted allochthonous (or “exotic”) terranes, whose origins were long a geological mystery, stretch from Alaska to South America. They not only augmented and built-out the continental landmass of the Americas, they also created many of the coastal mountain sections that we 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 (i.e., what is left of the ancient continent of Laurentia) from the Paleozoic to as recently as Late Miocene. However, many of these terranes are hidden beneath yougner deposited or erupted rocks. Although no allochthonous terranes have been positively identified in Arizona or Sonora, much of the Baja California Peninsula and western Mexico probably consist of these ancient relocated land masses. And the Baja California Peninsula itself, a continental block, or terrane, originating in central west Mexico, is destined to “reaccrete” to the North American continent sometime in the future.



The Colorado Plateau, Mogollon Rim, Lower Colorado River Basin, and the Upper Gulf of California (NASA)



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)

Thus, from the Mesozoic to the late Oligocene, the west coast of North America was bordered by an unbroken subduction zone—the Farallon Trench. Prior to the late Miocene Baja California was still attached to western North America. The subduction of the Farallon Plate beneath the North American Plate generated volcanism in the Sierra Madre Occidental, notably in two episodes,100-45 Ma and 34-23 Ma, and in what is now eastern Baja California and westernmost Sonora from 24 to ~9 Ma. As the Farallon Plate steadily subducted and disappeared beneath North America, the final phase of subduction resulted in a continental volcanic arc forming ~24-15 Ma. The rocks generated from this volcanic arc now constitute some of the uplifted mountains of the easternmost Baja California Peninsula (e.g., much of the Sierra La Giganta in Baja California Sur), but they are best seen in the mountain ranges in southwestern Sonora. The granitic batholiths of the modern Sierra Nevada range (California) also represent the eroded core of this ancient cordillera, whereas the chaotic coastal San Franciscan formations

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

are the remains of various islands, seamonts, sediments and metamorphic rocks accreted to the North American Plate as the Farallon Plate was subducted.

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

Throughout the Cretaceous and into the Cenozoic, the Farallon Plate grew narrower as it was consumed by the trench. By the Cretaceous, a wedge, or segment of the Pacific Plate and East Pacific Rise had begun pushing eastward into the heart of the Farallon Plate, sliding along the Mendocino and Murray Fracture Zones in the north and south. This section of the Pacific Plate (and its leading segment of East Pacific Rise) was moving eastward faster than the Farallon Plate was, thus forming a prominent eastward projection and slowly dividing the Farallon in half. Several microplates (e.g., Guadalupe and Magdalena Microplates) calved off the Farallon Plate as the leading edge of the Pacific Plate forced its way through it, and as the Farallon itself moved toward the subducting trench. Some of these smaller calved plate pieces still exist, and others were subducted long ago.

The central region of the Farallon Plate disappeared as the leading segment of East Pacific Rise met the North American Plate, ~25-30 Ma in central California, and ~11-15 Ma in northern Mexico. It was the collision of the East Pacific Rise with the west coast of North America that created the modern San Andreas Fault system. Thus the northern San Andreas Fault system formed ~27 Ma, the southern California section between 13 and 22 Ma, and the Gulf of California segment about 11 Ma. Today, the Mendocino Triple Junction marks the northern limit of the San Andreas Fault system, and the Rivera Triple Junction marks the southern limit.

This first contact of the East Pacific Rise with the North American Plate divided the Farallon Plate into northern and southern parts. The remnant microplates of the Farallon Plate, to the north and south, continue to move slowly against and under the North American Plate today. The existing northern remnants of the Farallon Plate are the Juan de Fuca, Explorer, and Gorda Plates (currently subducting beneath northern California, Canada, and Alaska). The southern fragments are the Rivera Plate (a microplate along the coast of Nayarit and Jalisco), Cocos Plate (currently subducting under southern Mexico and Central America), and the Nazca Plate (currently subducting under South America).

The Basin and Range Region and Opening of the Gulf of California

As the East Pacific Rise subducted beneath western Mexico, the edge of North America’s crust gradually became attached, and coupled to the Pacific Plate. Subduction had probably ended along the entire length of Baja California by ~12.5 Ma (Wijk and Abera 2017). The attachment began ~12 Ma in northwestern Mexico and was probably fully completed ~7 Ma. The coupling 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 Pacific Plate, with its attached segment from the North American Plate, thus continued to be driven westward by the East Pacific Spreading Ridge.

Transform boundaries (or "transform-fault boundaries") are where two plates are sliding more-or-less horizontally past one another. In these boundaries, large faults called fracture zones connect divergent plate boundaries (or, occsionally, trenches, in the case of convergent plate boudaries). Most transform faults are on the ocean floor, where they offset the active spreading ridges, produicg zig-zag plate margins. In some cases they occur on land, such as the 1300 km-long San Andreas Fault Zone, where the transform fault connects the East Pacific Rise, a divergent boudnary to the south, with the South Gorda/Juan de Fuca/Explorer Ridge, another divergent boundary to the north. The Pacific Plate has been grinding horizontally past the North American Plate along the San Andreas Fault Zone for over 10 million years, at an average rate of about 5 cm/yr. Land on the west side of the fault zone (on the Pacific Plate) is moving in a northwesterly dirction relative to the land on the east side of the fault zone (on the North Americna Plate).

By Late Miocene, ~7 Ma, most of the mountainous margin of northwestern Mexico had become coupled to the northwestward-moving Pacific Plate and had begun to pull away from the North American continent. However, the relative motion between these two neighbors (Pacific and North American Plates) is neither simple spreading nor convergence. Rather, the relative motion is described by plates sliding past one another (a transform plate boundary) along a northwest-southeast orientation, exemplified by the San Andreas Fault System in California.

In northwestern Mexico, the Pacific-North American plate boundary (the future Gulf of California) was oriented slightly more northerly to this relative plate motion. This resulted in relative plate motion that was oblique to the plate boundary, consisting of mostly transform motion (e.g., strike-slip faults) but also some extension. The resultant fault pattern includes discontinuous transform faults connected by short spreading segments that form new oceanic seafloor beneath the Gulf of California. It is the transform faults and spreading centers that together accommodate movements between the two great plates and, eventually, obliquely opened the Gulf.

Thus, the Gulf of California Rift-San Andreas Fault system was born. As this system developed, it stretched and thinned the continental crust. (Whereas oceanic crust tends to break, continental crust tends to stretch and thin.) A long period of extension across northern Mexico preceded formation of the Gulf of California. The initial rifting and crustal thinning took place in the middle Miocene ~13-7 Ma, creating an area of crustal subsidence in northwestern Mexico consisting of a Northwest/Southeast-trending extensional trough in the spreading region. Geologists named this trough the Proto-Gulf Extension, Proto-Gulf Rift, or simply the Proto-Gulf of California. The entire area has been called the Gulf Extensional Province, generally considered to extend from the eastern escarpment of Baja California's Peninsular Ranges, to the base of the pediment of the Sierra Madre Occidental.

It has been proposed that continental extension accelerated around 12 Ma, as subduction stalled offshore (Atwater and Stock 1998), setting the stage for lithospheric rupture and the onset of seafloor spreading around 6.3 Ma (Oskin and Stock 2003). This timing is supported by the presence of thick (~2 km) evaporite deposits under the shelf on the eastern margin of Guaymas Basin that correlate to similar gypsum beds near Santa Rosalía to the northwest on the Baja California Peninsula (Miller and Lizarralde 2013). One of the exposed gypsum beds near Santa Rosalía on the southern end of Isla San Marcos is ~8 km^2 in size and supports one of the world's largest gypsum mines (Founie 2007). Closing the Gulf along kinematic flow lines suggests that the Santa Rosalía gypsum beds formed on the edge of the Guaymas Basin evaporite deposit. The large volume of evaporites implies substantial marine incursions and subsequent evaporite deposition occurred ca. 7 Ma, just prior to lithospheric rupture. The formation of evaporites under conditions unique to continental rupture and the onset of seafloor spreading is well known (Evans 1978), and the Guaymas Basin-Santa Rosalía formation documents a late Miocene pre-rupture subsidence and associated shallow marine embayment event. The Santa Rosalía gypsums are underlain with limestones that contain late Miocene marine fauna, and Holt et al. (2000) estimated that these marine rocks were deposited 6.93-7.09 Ma (based on the age of an andesitic tuff that overlies the limestone and gypsum units). Miller and Lizarralde (2013) estimate the Guaymas Basin-Santa Rosalía marine incursions began just prior to ca. 7 Ma, about 0.5 to 1.0 Ma before the earliest marine incursions in the northern Gulf, and they refer to these early coastal depressions and associated marine incursions as "Proto-Gulf extensional basins." A similar setting of marine incursions and evaporite formation has been invoked to explain the thin gypsum deposits in the Northern Gulf (Escalona-Alcázar et al. 2001).

The Proto-Gulf concept was originally used by Moore and Buffington (1968) to explain an area of anomalously old oceanic crust adjacent to the eastern margin of the mouth of the Gulf of California—thus it was a tectonic/geological concept. It might have been Karig and Jensky (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 active trench-arc systems."

Subsequently, however, the term Proto-Gulf has occasionally been inappropriately used, usually by biologists but sometimes also by geologists, as a synonym for the presence of early, pre-Gulf of California basins and associated marine incursions into the region. However, the term should properly be restricted to the geological, extensional event that created the Gulf Extensional Province ~13 to 7 Ma. The modern Gulf of California, on the other hand, is a product of seafloor spreading and transform faulting since ~8 Ma. Inconsistent use of the term "Proto-Gulf" has led to a great deal of confusion for students of the Sea of Cortez and Baja California Peninsula. Unfortunately, many authors have carelessly used the term, often without even defining what they mean by it and commonly confusing evidence for pre-Gulf embayments of the Pacific Ocean onto mainland Mexico with the later-developed Gulf opening. (See discussion below.) In fact, the opening of the Gulf is a textbook example of the processes that take place during the early stages of formation of an ocean basin.

A distinct style of rifting occurs along the active tectonic margins of continents, and these rifts often create marginal seas or continental blocks (or slivers) that are ruptured away from their home continent. This is precisely how the Gulf of California formed, as the Baja California "Microplate" ripped free of the North American Plate. In the southern Gulf, sea-floor spreading commenced only ~6 million years after the formation of the oblique-divergent plate boundary at ~12.5 Ma. This rapid (in geological terms) rupture is thought to have been driven by the long, narrow belt of hot, weak crust from the volcanic arc that was active immediately before formation of the divergent plate boundary and that lay between two strong batholith belts, combined with the strike-slip faulting in the oblique-divergent setting that formed large pull-apart basins with rapid crustal thinning. Pull-apart basins are characterized by rapid subsidence of hundreds of meters to several kilometers per million years (Xie and Heller 2009).

A river in the Sierra La Giganta, west of Loreto, central Baja California Sur. The exposed rocks are part of the volcanic arc created by subduction of the Farallon Plate 24-15 Ma.

Studies suggest 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 around the northern and southern ends of the Sierra Madre Occidental (e.g., Henry and Aranda-Gomez 2000). Batholiths generally resist extension, and the Henry and Aranda-Gomez (2000) 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 Geological 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 (west of the Sierra Madre) borders the Gulf of California and 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.

So, we see that the Gulf Extensional Province and the geological Proto-Gulf were part of the same pulses of crustal extension that created North America's Basin and Range Geological Province. All of this being driven by the extension created after 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 also some evidence that rapid, large-magnitude extension pulses were associated with broadscale 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 around 450 mountain blocks of exposed, ancient rocks and intervening valleys known as the Basin and Range Geological Province, which spans as far north as Oregon, and southward into west-central Mexico. The basins are down-dropped blocks of continental crust; the ranges are blocks that were uplifted relative to (and bordering) the fallen blocks. Due to this 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 Ma. Similar ages have been obtained from basalts of the Baja California Peninsula.

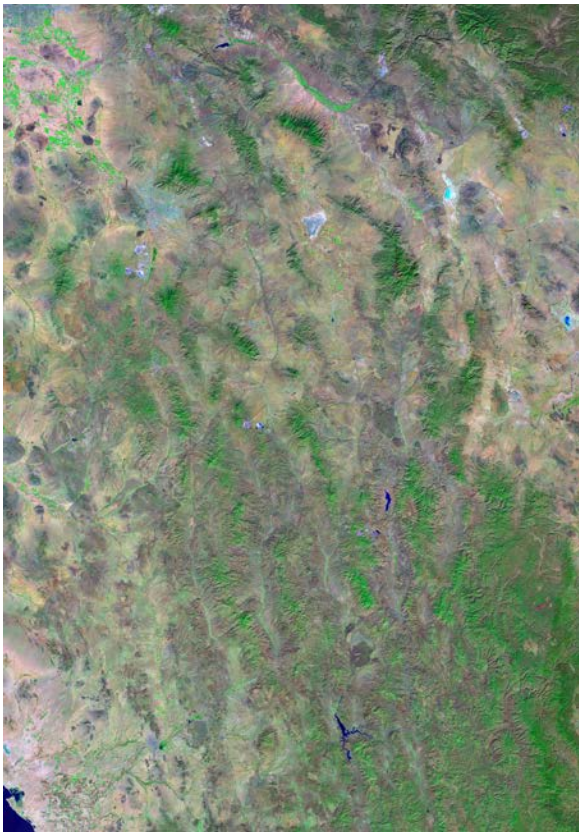
The precise timing, magnitude, and distribution of crustal extension in the Basin and Range Province is still being worked out. The total amount of extension was perhaps 50-100% (i.e., up to a doubling of width of the crust in the region), but this occurred unevenly throughout the Province, and less 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 occurred throughout 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, as mentioned, the Sierra Madre Occidental shows almost no evidence of extension. Almost all of the extension in Sonora occurred between ~25 and 10 Ma, with the age of the extension decreasing from east to west.

As the crust of western North America thinned, the Proto-Gulf of California Extension grew, allowing for the possibility of one or more, temporary, marine transgressions, or incursions of the Pacific Ocean onto mainland Mexico, between ~13 and ~7 Ma, <u>before</u> formation of the Gulf of California. Such a marine incursion could have resulted from a marine back-arc basin that connected to the Pacific ocean via a seaway. These embayments, or seaways would have probably looked similar to the ancient seaway in California that once filled that state's great Central Valley.

As noted above, it has sometimes been said (or implied) that these marine incursions or embayments should be regarded as a "Proto-Gulf" but this is incorrect. Any embayments would have occurred before the Baja Peninsula separated from mainland Mexico, and before the Gulf of California was formed. There is no physical evidence that any seaways have ever existed that had a connection to the modern Gulf of California. A few authors have interpreted the sedimentary and paleontological data of putative middle 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 numerous lines of tectonic and geological data support the idea that the Baja Peninsula was attached to mainland Mexico until ~7 Ma. 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 lack of evidence for marine rocks between ~12 and 6.3 Ma for the entire northern Gulf, suggesting that a marine basin did not exist during that time (Endnote 3). In fact, evidence suggests that detachment faulting and continental rupture in the Northern Gulf was delayed, perhaps due to the effects of the thick deposits of Colorado River sediment (Martín-Barajas et al. 2013).



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 late Miocene (?) and early Pliocene Bouse Formation is a patchy fossiliferous mix of lacustrine sediments buried beneath the more recent Colorado River gravels. It outcrops (and is present in the subsurface) along the lower Colorado River Valley of western Arizona, southern Nevada, and southeastern California. It ranges from less than 10 m thick outcrops, to over 250 m in subsurface wells. The mix of lakebed sediments with scattered marine fossils confused interpretation of the Bouse Formation for many years, but modern interpretations (e.g., Roskowski et al. 2010, Cohen et al. 2019) suggest 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), as occurs in the Salton Sea today. Roskowski et al. (2010) argue strongly against marine influence anywhere in the Bouse depositional system, instead hypothesizing an interconnected chain of lakes fed by the Colorado River. As river water arrived in each basin, it began depositing 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 4-6 Ma (Spencer et al. 2013a,b; Cohen et al. 2019). Only one marine fish fossil has been described from the Bouse Formation, *Colpichthys regis* (the "false grunion"). Chapin (2008) suggested that intensification of monsoonal flow up the newly formed Gulf of California, and the resulting increase in precipitation, may have accelerated the overtopping of the lakes that drove the river toward the upper Gulf.

Expanding on this model, McDougall and Miranda Martínez (2014) reported evidence for a sequence of events in the Bouse Formation of the Blythe Basin in which there occurred: (a) a late Miocene extension of the Gulf of California, (b) a subsequent restriction (or elimination) of the marine connection, (c) establishment of a saline lake (with the only marine survivor evident in the upper Bouse deposits being the euryhaline foraminiferan *Ammonia beccarii*), and finally (d) spilling of the lake into the Salton Trough and the Colorado River becoming a through-flowing river.

The sediments of the Colorado River that fill the basins of Southern California and northwestern Mexico are so large that they are heated at their depth, to form recycled crust along the active plate boundary. The volume of river-derived sediment in these basins has been estimated to be between 2.2 and 3.4 X 10^5 km^3, similar to the volume of rock that was likely eroded by the Colorado River and its tributaries over the past 5-6 million years (Dorsey 2010).

The Altar Basin lies between the town of San Luis Río Colorado (in the north) and Bahía Adaír (in the south). The basin's origin was an extension event that began sometime after ~16 Ma. The basin was once part of the Colorado River Delta, and today its surface is still subject to flooding even though it carries the aeolian dune field of the Gran Desierto.

Three major sedimentary sequences have been identified in the Altar Basin. 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 Ma) 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. Thus the Altar Basin shares with the Salton Trough and the Cerro Prieto Basin a historical sequence of: (1) an initial period of extension and subsidence, (2) an intermediate stage of marine sedimentation, and (3) a later period of non-marine sedimentation.

Pliocene dated Colorado River gravel deposits are abundant throughout the Lower Colorado River Basin, in Arizona, California and Mexico. They have been mapped from the Lower Coachella Valley-Salton Sea-Imperial-Mexicali Valleys, and east into the Yuma Valley. In the Yuma area (e.g., Yuma Proving Grounds) they form unconsolidated sheets up to 10 m thick that are largely exposed, at elevations of up to 60 m above the present river level (Nations and Gauna 1998). In many areas, desert pavement and varnish are well developed on the exposed surfaces. Most of the gravels and sands have a Colorado Plateau source, and they are well rounded and moderately sorted, due to the distance they have traveled. In the Yuma area, the gravel deposits usually sit atop Pliocene Colorado River sediments (sand and silt) that comprise the Bouse Formation, which may be 100 m thick, and these in turn lie atop pre-Colorado River non-marine deposits (including the Kinter Formation).

Near the head of the Gulf of California, early to middle Pleistocene Colorado River gravels have been raised around the town of El Golfo de Santa Clara by the active San Jacinto-Cerro Prieto Fault system (e.g., the ~200 km^2 El Golfo Badlands), where they contain a diverse vertebrate fauna and abundant petrified wood (summarized in Lindsay et al. 1980, Shaw 1981, and Davis et al. 1990). Age estimates for the Colorado River gravel deposits are between 2.8 and 4.0 Ma, the older date possibly recording the Colorado River's first arrival into the Salton Trough. The change from finer-grained Bouse Formation sediments to coarser gravels represents a large energy increase. Following deposition of Colorado River gravels in the Yuma area, as recently as 2.8 Ma, the river changed course and followed a new channel across the southeastern end of the Chocolate Mountains (in California).

By 6.5 - 7 Ma, rifting of the Baja Peninsula obliquely away from the mainland had begun. 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 plate boundary and are part of the northwest-moving Pacific Plate. Since 7 Ma, the peninsula has moved about 300 km northwestward (from the mainland at the southern end of the Gulf) and it continues to obliquely open at a rate of about 4.6 cm/yr. As the peninsula and Southern California continues to move northwestward, San Diego-Los Angeles-Santa Barbara move closer and closer to San Franciso!

Isla Tiburón, in the Midriff Region of the Gulf, is on the North American continental crust, east of the spreading zone, and its marine sedimentary outcrops are the only exposed Miocene marine record along the eastern margin of the Gulf of California. These marine strata, originally dated as middle Miocene, have been cited as evidence for a middle Miocene marine incursion into the Gulf 7 – 15 Ma. This interpretation played a large role in subsequent views of regional tectonics, rift evolution, and putative "trans-peninsular seaways" across the Baja California Peninsula (now definitively shown to have never existed). The dates have also influenced age interpretation of marine deposits at other locations, from throughout the Gulf and into the Salton Trough, including the Imperial Formation. However, more recent work by Oskin and Stock (2003) and Bennett et al. (2015) has shown that the middle Miocene dates on these deposits were in error, and they are actually latest Miocene/early Pliocene in age, 6.2 – 4.3 Ma. This corrected timing supports the view of a straightforward south-to-north marine incursion into the Gulf as it opened, consistent with a well-documented record of a latest Miocene (ca. 6.3 Ma) marine incursion into the northern Gulf and Salton Trough, and also consistent with the well-documented dates of 8.2 to 7 Ma for earliest marine strata in the southern Gulf, and it does not lend support a trans-peninsular seaway concept.

At 8 Ma, the earliest marine conditions in the Gulf comprised an embayment at its southernmost mouth (Umhoefer et al. 2018).

By 7 Ma, a series of marine incursions breached across strike-slip faults to the Pescadero and Farallon Basins. Marine waters then breached a 75-100 km-long fault zone between the Farallon and Guaymas Basins, with intermittent flooding that led to accumulation of evaporite deposits in the Guaymas Basin. Further incursions to the north breached the Guaymas and Tiburón strike-slip faults and resulted in flooding of the northern >500 km of the oblique rift by 6.5-6.3 Ma.

Bennett et al. (2015) argue that other alleged middle Miocene marine deposits (e.g., from the northern Salton Trough, Cerro Prieto, Laguna Salada, and from borehole cuttings in Sonora) probably represent reworked material from elsewhere in the region or incorrect dating. No middle Miocene marine rocks occur in the mountain ranges that flank the Sonoran coastline today, despite evidence of significant faulting and tilting. In fact, no outcrops of middle Miocene marine strata are known anywhere in western Mexico, despite the documented presence of non-marine strata of the appropriate age.

Once the peninsula separated from the mainland, spreading-center seafloor basins formed along the entire length of the southern Gulf, including the Alarcón Basin, and on to the Pescador, Farallón and Guaymas Basins, and eventually to the far northern (and younger) Tiburón, Lower Delfín, Upper Delfín, Wagner and Consag Basins. These are all still active rift basins, although those in the Northern Gulf are buried under many kilometers of Colorado River sediments and the extent of spreading is still being debated. Both the Wagner and Consag Basins have been shown to have intense gas hydrothermal activity (Canet et al. 2010). Although the Wagner Basin is the northernmost spreading center in the Gulf, the northernmost basin in which true oceanic crust has been identified is the Guaymas Basin. Inactive basins have also been located in the Gulf, including Adair, Tepoca, and Tiburón Basins.

The huge Wagner Basin was recently mapped at ~1330 km^2 (González-Escobar et al. 2009). It is bounded on the west by the Consag Fault, and on the east by the Cerro Prieto and Wagner Faults. The Upper Delfín Basin (east of Puertoecitos) has been studied by Oskin and Stock (2003) who suggested the basin opened ca. 6 Ma as a narrow zone of divergence between the Pacific and North American Plates.

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 oceanic rifts bordered by alternating bands of magnetically oriented/polarized basalt. Similar magnitudes of rifting occurred in the northern Gulf and Salton Sea, forming pull-apart basins, including the Wagner, Consag, Altar, and Salton Basins. However, formation of oceanic crust in the Northern Gulf was either thwarted or delayed for seveal million years as these pull-apart basins were drowned with several kilometers of sediment input fom the Colorado River. The Gulf thus occupies a large rift valley between the Pacific and North American tectonic plates, and it can be viewed as a transitional corridor that connects the East Pacific Spread Ridge to the San Andreas Fault Zone in California.

The Guaymas Basin is a narrow rift segment with high magma production and hydrothermal vents, and its lithospheric rupture probably occurred somewhere between 3 and 6 Ma. The Alarcón segment is a wide rift that probably began 2-3 Ma. Due to the difficulty of studying the Wagner and Consag Basins, which are buried under ~7 km of sediments (the underlying crust is only ~15 km thick), these basins have only recently been shown to be active spreading centers with hydrothermal activity. These two shallow (~225 m below sea level) 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 relatively short amount of time to rupture continental crust and form oceanic crust in the Gulf has been attributed to three probable factors (Umhoefer 2011). First, the thinned and weakened 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, the rapid rate of plate motion associated with the Baja Peninsula moving away from mainland Mexico. And third, the oblique nature of the movement along this plate boundary, which resulted in the establishment and dominance of strike-slip faulting that formed pull-apart basins. The strike-slip faulting and focused crustal thinning in pull-apart basins.

Some workers consider today's Baja California Peninsula (and its associated segment of California) as a "microplate," because it is not entirely "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. Evidence suggests

The Gulf of California and Baja California Peninsula from space (NASA image). In this image, strong easterly winds are blowing dust off the Plains of Sonora and Vizcaino Desert of the Baja California Peninsula.

that the entire peninsula (at least from the latitude of Ensenada southward) has remained essentially rigid from Miocene time to the present. A proposed transpeninsular strike-slip fault in Baja California Sur has not been conclusively validated. California's southern coast and southern Peninsular Range were uplifted coincident with

Pliocene-Pleistocene movements of peninsular Baja California.

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 and connected spreading centers sometimes referred to as the Gulf of California-Salton Trough Rift. 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 200 km (125 mi)-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 4). The Colorado River Delta largely fills the depression of the Salton Trough.

The Salton Trough is a pull-apart graben, 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). In the case of the Salton Trough, the graben has filled with more than6 km (3.7 mi) of sediments eroded from adjacent mountain ranges as it has subsided. Although not restricted to rift valleys, grabens are characteristic of them.

The Salton Trough is essentually the northernmost part of the Gulf of California rift, the northern boundary being San Gorgonio Pass near Palm Springs (California), at the north end of the peninsular ranges of California. The Trough is mostly below sea level today and consists of California's Coachella and Imperial Valleys, and Mexico's Mexicali Valley. The Salton Trough is the only active part of the Gulf of California rift that is not covered by ocean water today. It would be beneath water were it not for the barrier, or sill, of the 8612 km^2 (3325 mi^2), 5.6 km (3.5 mi)-deep Colorado River Delta sediments. The trough itself covers more than 5180 km^2 (2000 mi^2).

About 25 km (16 mi) 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 Late Miocene to Early Pliocene. In fact, foraminiferan fossil strata suggest the Gulf may have extended all the way to the San Gorgonio Pass when it first formed. During much of the Pliocene, sea levels were much higher than today, and evidence of Pliocene embayments occurs throughout the coasts of the Gulf of California, and even on many of its islands (Endnote 5).

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

About 5.5 Ma, the path of the Colorado River ended far north of where it meets the sea today. We know this 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 Ma). By 3 to 4 Ma, the river mouth had moved southward to the Yuma area.

Today, 3–6 km (2–4 mi) of Miocene and younger sediments overlie the oceanic-continental crust of the Salton Trough, which continues to subside at a rate of 1–2 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 across these basement rocks is comparable to that of Mt. Everest! The lowest point in the Salton Trough today is the Salton Basin, which is 69 m (226 ft) below mean sea level. The southern Salton Trough includes Laguna Salada and the Mexicali Valley, separated from one another by the Sierra Cucapa-Sierra Mayor. Laguna Salada is at least 11 m (36 ft) below mean sea level.

The San Andreas-Gulf of California Fault System is the geologically complex boundary between the Pacific and North American Plates in this part of the world. Evidence suggests that at 1.5 Ma 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 at the latitude of 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. The northern tip of the Baja California microplate currrently sits at San Gorgonio Pass, near Palm Springs, California. This pass is a deep gap on the rim of the Great Basin between the San Bernardino Mountains to the north, and the San Jacinto Mountians to the south. Interstate 10 and the Union Pacific Railroad run through the pass, connecting the Coachella Valley to the Los Angeles Basin. It is one of the deepest mountain passes in the 48 contiguous states, with mountains on ether side rising to nearly 9000 feet. Part of the San Andreas Fault system, the pass is the major geolgic divide between the igneous batholith of the Peninsular Ranges and the Transverse Ranges (a massive block fault). It is the single largest discontinuity along the San Andreas Fault.

The San Andreas-Gulf of California Fault System comprises numerous transform faults, or “strike-slip faults,” with 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. The onshore portion of the San Andreas Fault System runs from the

A view of San Gorgonio Pass (filled with smog from the Los Angeles Basin), the northern boundary of the Salton Trough. Photo by Don Bethel.

southern end of the Salton Sea to Point Reyes just north of San Francisco. To the north of Point Reyes, it continues offshore as a 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.

The San Andreas Fault System was reorganized in the early Pleistocene from a system domianted by two fault zones (the San Andreas Fault and the West Salton Detachment Fault) to a network of dextral faults that include the San Andreas and at least four dextral faults to the southwest. The San Felipe Fault Zone, one of these dextral faults, consists of three principal faults in the Peninsular Ranges (Steely et al. 2009). These are the San Felipe Fault in the WNW, Sunset Fault in the middle, and Fish Creek Mountains Fault in the ESE. In the south, the fault system continues beyond the Salton Sea, and through the Gulf of California to where it joins the Rivera Triple Junction (southeast of the tip of the peninsula, where the North American, Pacific, and Rivera Plates meet).

On April 4, 2010, an Mw 7.2 earthquake rocked the Mexicali Valley. The El Mayor-Cucapah Earthquake was centered at a depth of 10 km (6.2 mi), 47 km (29 mi) south-southeast of Mexicali. It was the largest seismic event in the area since the 1892 earthquake, even larger than the 6.9 event in 1940. The El Mayor-Cucapah quake caused liquefaction over most of the Mexicali Valley, leading to the collapse (or near collapse) of hundreds of buildings, as well as collapse of a railway bridge over the Colorado River, destruction of irrigation canals, and disruption of agricultural lands with sand “volcanoes” and ejecta spread over the ground surface. The main event triggered seismicity along the Elsinore and San Jacinto faults to the north. There were two human fatalities directly caused by the earthquake. The event was preceded by many foreshocks in March and early April. The El Mayor-Cucapah Earthquake was an expression of regional tectonics associated with the westward growth of the Mexicali Valley and the transfer of Pacific-North American Plate motion from the Gulf of California in the south into the southernmost San Andreas Fault System to the north.

The spreading process under the Gulf's waters has resulted in both thinning of the Earth's crust and development of deep sea-floor hydrothermal vents. These vents have probably been present since the Late Miocene and many persist today, such as those in Pescadero Basin, Guaymas Basin, Wagner Basin, and along Alarcón Ridge, where geothermal liquids and gases discharge through fractures in seafloor rock and overlying sediments. Shallow hydrothermal *vents* also occur in at least three locations in northwest Mexico: Bahía Concepcion (east coast of Baja, in the central Gulf); Punta Mita, Banderas Bay (Nayarit); and Punta Banda (on the Pacific coast of Baja California).

Hydrothermal *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 hydrothermal hot springs occur in the intertidal and shallow subtidal zones where people occasionally use them as a source of fresh water and for bathing (Endnote 6). The Bahía Concepción vents, which occur in waters up to 13 m (43 ft) deep, occur in a line nearly a mile long, roughly paralleling the El Requeson Fault on the west side of the bay. The famous old Buena Vista Fishing Resort, between La Paz and Cape San Lucas, for many decades has used water from a hydrothermal spring that runs under the hotel. Certainly many hydrothermal springs remain to be discovered in the Gulf. These coastal springs discharge heated water (to >90º C) derived from a mix of seawater and groundwater (from shallow water tables). 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 cm (~6 inches) of the discharge, and other invertebrates begin to appear a bit farther away.

Over the past two million years, the world experienced multiple sea level changes in response to galcial-interglacial cycles and associated changes in ocean volume. In the eastern Pacific, during the last major interglacial period ~125,000 years ago, sea level was higher than today. In the Northern Gulf this high shoreline created what are recognized today as ridges of concentrated shells (especially *Chione*) or cheniers 5-7 m above current sea level (Ortleib 1991). Ancient, higher than present sea levels are also indicated by subsurface coquina beachrock located beneath eolian sands several hundred meters inland from Estero de Morúa, near the town of Puerto Peñasco (DeCook et al. 1980).

During the height of the Last Glacial Maximum, ~21.5 ybp, relative sea level was approximately 130 m lower than today (Jansen et al. 2007), and sea level in the Northern Gulf would have been 50 to 80 km offshore, near the Wagner Basin (van Andel 1964, Bischoff and Niemitz 1980). Coastal archeological sites from that time would thus be under water today. Clovis sites such as El Fin del Mundo indicate humans were in Sonora as early as 13.4 ka (Sanchez et al. 2014) at a time when relative sea level was ~80 m below modern levels. Van Andel (1964) and Thompson (1968) not that “during the Wisconsin lower sea level” most of the Upper Gulf was exposed subaerially and the two large channels leading to Wagner Basin were cut by the Colorado River. Thompson (1968) further speculated that a standstill interrupted the late Wisconsin rise of sea level and resulted in the formation of an older intertidal mud flat in the western Gulf, recognizable today as a terrace at depths of 1- - 15 m offshore from San Felipe. Both the two ancient drainages to Wagner Basin and the ancient intertidal mud flat are recognizable today in sonar profiles of the Upper Gulf seafloor.

Sea level rose rapidly after 16 ka as oceans warmed and glaicers melted (Smith et al. 2011). Between the occupation at El Fin del Mundo and the earliest ^{14}C dated shell midden material in Northern Sonora (6.0 ka), sea level rose approximatelty 75 m at a rate of about one centimeter per year.

On the Sonoran-Sinaloan coast in northwestern Mexico, surprisingly little uplift has accompanied the extensive horizontal movement over the past 6 million years, though there has been recent (early to mid-Pleistocene) uplift of up to 150 m (164 ft) along the eastern margin of the Colorado River Delta, driven by the Cerro Prieto Fault (which runs from the Salton Trough and Mexicali Valley into the Gulf of California). This uplift, in combination with high sea level stands during the Pleistocene, created the Mesa de Sonora (Davis et al. 1990).

Less dramatic uplifted Pleistocene beach terraces, 7–25 m (23–82 ft) above mean sea level, can be seen in northern Sonora along the coast from El Golfo de Santa Clara southeastward to northern 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 years-before-present (ybp) high sea-level stand, or might reflect an earlier interglacial shoreline present 125,000 ybp (the last major interglacial period), 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, mostly between El Golfo de Santa Clara and Salina Grande (in Bahía Adiar), is likely the result of drag-folding directly related to Cerro Prieto Fault activity beginning ~1 Ma and continuing today. This “doming” event reuslted inuplift and exposure of Pleistocene eoliian, fluvial, deltaic, and shallow marien depsoists as nearly continuous beach cliffs (Ortlieb 1987, Lock et al. 1989, Cutler and Meldahl 1990). The Mesa de Sonora marine terrace, 50-150m (164-492 ft) 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 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. On the Vizcaino Peninsula of western Baja California there are two well-described marine terraces, known as the Sangamon Terrace and the "*Tivela stultorum"* Coquina. The former occurs around several rocky headlands of the southern peninsula and is about 5 m above present mean sea lefel. It is the lowest marine terrace in the region and has a well preserve fossil fauna. The Sangamonian is estimated to have formed between 120,000 and 80,000 years ago. The "*Tivela stultorum*" Coquina is, as the name implies, rich in shells of the Pismo clam (or something that looks very much like it). It out-crops in Bahía de San Hipolito and Bahía de Asunción as poorly consolidated, sandy beachrock a few meters thick, 15-20 m above present mean sea level. Older Pleistocene marine deposits have been reported up to 130 m elevation, and even 250 m elevation, but these are not well undersood.

Globally, these exposed traces of old beaches and rocky shorelines generally correspond to high sea-level stands of previous warm episodes or the glacial minima of the Quaternary. Three globally recognized terraces have been documented from the last interglacial period (known as marine isotopic stage [MIS] 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 of identified marine terraces above current sea level allows one to calculate how much relative coastal uplift has occurred. The MIS 5e terrace/shoreline can be seen at a nearly constant elevation of ~5-7 m (16.5 to 23 ft) between Bahía Adair and Guaymas, and it seems to have had an uplift of no more than 1-2 m (3.3 to 6.5 ft) 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 the Puerto Peñasco area there are ridges of concentrated *Chione* shells 5-7 m above current seal level estimated at 125,000 ybp (Ortleib 1991). There are also deposits of subsurface coquina beachrock located beneath eolian snad dunes several hundred meters inland from Estero de Morua (near Puerto Peñasco) (DeCook et al. 1980). At the height of the Last Glacial Maximum (21,500 ybp) sea level was ~130 m lower than today (Jansen et al. 2007), and the shoreline would have been ~70 km offshore from where it is today (near the edge of Wagner Basin). Two prominent seafloor channels run on the west and east sides from the uppermost Gulf to Wagner Basin, and these might be remnants of former Colorado River drainages during lower sea level stands (Thompson 1968).

In contrast to the generally low-relief Sonoran coast, steep relief and outcrops of volcanic rocks 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. The contrast in ancient shoreline expression, uplift, and relief is due to the fact that the eastern Baja shoreline is proximal to active rifting, presently concentrated in the western Gulf, and rifting-related faulting and uplift near the eastern Gulf shore (Sonroa) has been mostly inactive for several million years. 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 observed. 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 (1,083 ft) of uplift (probably all Quaternary) and about 14 distinct stage 5e terraces almost regularly spaced vertically, with 25 m (82 ft) height differences between them.

The Baja California Peninsula itself is an excellent example of a continental block, or terrane, that has moved hundreds of kilometers along a highly oblique divergent plate. It is a buoyant continental block that is likely to be preserved in any future accretion to the North American continent.

The peninsula (and the seafloor of the Gulf) can be divided into three major domains on the basis of the active transform faults in the Gulf (Umhoefer and Dorsey 2011). The northern domain runs from Puertecitos to the Salton Trough, and many strike-slip faults diverge to the west from the transform faults of this region to cut across Baja California and Southern California (Saurez-Vidal et al. 1991). The central domain runs from ~30°N to ~25°N, and there are no faults cutting across Baja California in this region (Umhoefer and Dorsey 2011). The southern domain runs from ~25°N to the mouth of the Gulf and has many seismically active normal and oblique faults that cut through Baja California (e.g. La Paz Fault; Normark and Curray 1968). The numerous faults of the northern and southern domains are inherited from the evolution of the plate boundary, which jumped from west to east over the past 15 mya (Lonsdale 1989, Suarez-Vidal et al. 1991).

There is a nearly continuous exposure of rocks of the Miocene volcanic arc for more than 400 km from near La Paz to 28°N (Sawlan 1991), and similar volcanic rocks are exposed discontinuously to at least 31°N (Gastil (et al. 1975). North of 30°N, widespread exposure of Cretaceous magmatic arc and fore-arc rocks occurs, confirming that no large strike-slip faults cut across the central domain (Gastil et al. 1975, Umhoefer and Dorsey 2011). In the central domain, the peninsula can be divided into two parts from west to east. The western part is largely unfaulted gently inclined strata of the Miocene fore-arc and older units. The eastern edge of the peninsula (and the narrow shelf in the Gulf) are part of the Gulf extensional province

The El Golfo Badlands, on the Mesa de Sonora, east of the fishing village of El Golfo de Santa Clara

The volcanic rocks that make up the headlands on the coast of Sonora, such as the 15 million-year-old Punta/Cerro Peñasco (at the town of Puerto Peñasco) and nearby Cerro Prieto ("Black Mountain") headlands, predate the opening of the Gulf and are remnants of ancient mid-Miocene interior volcanism related to subduction of the Farallon Plate (Lynch 1981).

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 ~6-7 Ma. The oldest marine incursion dates, based on localized outcrops and exploratory wells drilled in the northern Gulf, are Miocene and have been estimated at 14–11 Ma. 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 Ma. Similar dates for a marine incursion have been reported from the San Felipe area (NE Baja California) and on Isla Tiburón. However, revised interpretations of these marine strata, the fossils contained within the strata, and precision age-dating of volcanic roks below and above these marine deposits point to a yougner, late Miocene age (see Stock 1997, and Bennett et al. 2015). Late Miocene (6.0 – 5.5 Ma) 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).

While it is possible that Miocene incursions took place between 13 and 6 Ma, no marine rocks between 12 and 6.3 Ma have been identified throughout the northern Gulf/Salton Trough (see Endnote 3). It has been suggested that 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.

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

Ledesma-Vázquez (2002) has hypothesized a large early Pliocene (5 Ma) embayment in the central pre-Baja Peninsula, near Laguna San Ignacio. His model suggests that the Gulf had not yet opened that far north, and the embayment disappeared (due to tectonic uplift and volcanism) before the Gulf extended north to its present extent. Thus, this putative embayment also would have afforded no connection between the open Pacfic and the modern Sea of Cortez.

There are about 2 dozen named ranges on the Baja California Peninsula, the two highest being the Sierra de Juárez and Sierra San Pedro Mártir. The uplift of Sierra San Pedro Mártir, and the other Peninsular Ranges, probably began ~6 Ma, 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 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. The southernmost limit of the delta is the large Isla Montague, visible on the lower right side of this image.

Some workers have hypothesized a Miocene Gulf that extended well into southern California and then retreated to its present configuration during the Pleistocene, but geological data do not support this early opening of the Gulf of California.

Wave-rounded basalt rocks and boulders on the beach at Punta Peñasco, Sonora

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 Pliocene or Pleistocene transpeninsular seaway in the central Baja California Peninsula (largely summarized in Riddle et al. 2000). However, more recent work has challenged the seaway-vicariance hypothesis, and numerous questions of timing and cauality between biota and putative vicarieant evetns reman unanswerd (summaried in Dolby et al. 2015).

There is no evidence of a sea-level rise, in and of itself, sufficient to accommodate such complete transgressions over the past 6 Ma—a 300 m (984 ft) rise, or more, would be required. Uplift rates of ≥0.2 mm/year could have elevated low passs across the peninsula (e.g., near Santa Rosalía) that could have hosted a transpeninsular seaway 1-2 Ma. However, uplift rates of this magnitude have not been documented this far south on the peninsula. So if the genetic patterns are meaningful, other explanations should be sought. Valdivia-Carrillo et al. (2017), for example, noted the strong climatic heterogeneity of the peninsula and suggested it influenced the population genetic structue of terrestiral desert iguna and other animals (rather than vicariance).

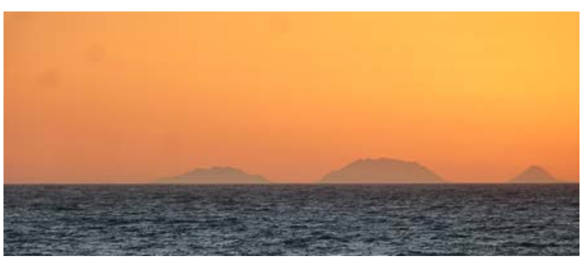
It could be that the genetic patterns were established earlier in the Miocene when the documented marine embayments could have driven vicariance/speciation events for coastal land vertebrates before the peninsula formed. Such vicariant patterns could then remain detectible on the peninsula subsequent to its establishment.

Another explanation for genetic breaks in modern small-vertebrate populations on the peninsula 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. 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 trans-peninsular seaway from the Pacific Ocean to the Gulf of California and, in fact, many studies have found data that contradict putative seaways (Endnote 7).

The modern Gulf of California comprises an 1300 km (800 mi)-long peripheral extension of the eastern Pacific Ocean, varying from ~120 km (75 mi) wide at its mouth to ~50 km (30 mi) in the north, enclosing a marine surface area of ~210,000 km^2 (82,000 mi^2) and a shoreline of 7000 km (4350 mi), including island coastlines. The present Baja California

Peninsula is 1450 km (900 mi) in length and covers 145,000 km^2 (56,000 mi^2). Thirty-eight percent of the peninsula's Gulf coastline is in the state of Baja California, 62 percent in the state of Baja California Sur.

The Santa Rosalía area has been particularly active volcanically. The writings of Jesuit father Ferdinando Consag date the most recent eruption of the Tres Vírgenes Volcanos complex (La Vírgen, El Azufre, El Viejo), located just north of the town of Santa Rosalía, as summer 1746. There was also a possible eruption in 1857. Just east of the Tres Vírgenes is the massive La Reforma Caldera, which is about 10 km in diameter and at an elevation of 1300 m. Isla San Luis was volcanically active as recently as ~1200 years ago, and remains potentially active today; here, the crater rim of an old volcanic cone rises 180 m above sea level. The small (2.9 mi^2) but exquisite 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 (853 ft) high cone of an extinct volcano.



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

Estimates put the last activity of the Coronados volcano at just 160,000 ybp. In addition to 12 Ma andesite flows and a young (Pleistocene) volcano, Isla Coronados also harbors a large and well-developed Late Pleistocene coral reef.

One of the most interesting, but poorly studied, fossil deposits on the Baja Peninsula is the so-called Trinidad Formation, in the San José del Cabo Basin of Baja California Sur (located between the Sierra La Laguna and Sierra La Trinidad). It has been suggested that these uplifted deposits likely preserve an offshore sea bottom of at least 100 m depth that was poorly oxygenated and lacked strong currents (Fierstine et al. 2001). The only fossil billfish (blue marlin, *Makaira* sp., *cf. nigricans*) known between southern California and Panama occur here, as well as several mollusc species. However, the presence of two bivalve species, *Anadara* sp. and a rock oyster (*Crassostrea gigas* ?), suggests a depth shallower than 100 m (see below). This deposit has been estimated to be Upper Miocene to Upper Pliocene in age.

Outer and inner aspects of the bivalve *Anadara* sp., from the Trinidad Formation of Baja California Sur

Outer and inner aspects of the oyster *Crassostrea gigas*(?), from the Trinidad Formation of Baja California Sur; length 12 cm.

Islands in the Sea of Cortez

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*. But many of the islets and rocks remain unnamed.

During the rifting process that formed the Gulf of California, numerous islands were formed as they broke off the peninsula and mainland. This is a typical consequence of the extension and rifting process, as fragments of continental curst were left in the wake of the northwest-moving Baja Peninsula. These islands include Islas Carmen, Danzante, Coronados, Monserrat, Santa Catalina, San José, and Espíritu Santo.

Other islands are the result of recent volcanism, including Islas San Esteban, San Pedro Mártir, San Pedro Nolasco, San Luis and Tortuga. San Pedro Nolasco is unique among the Gulf islands in its exposure of 9 to 10 Ma intrusive rocks, and the island is the result of transtensional faulting of the late Miocene Gulf of California shear zone before the westward migration of the North American-Pacific plate boundary ~2-3 Ma (becoming an island during the late Miocene flooding of the Gulf of California seaway) (Velderrain-Rojas et al. 2022).

The low-lying Isla San Ildefonso, in the Sea of Cortez

Isla Ángel de la Guarda, the second largest island in the Sea of Cortez, was once attached to the Baja Peninsula. Somewhere between one and six million years ago activity on a regional fault zone (the Delfín Basin Spreading Center) pulled it, and probably also Islas Partida Norte, Salsipuedes, San Lorenzo Norte and Sur, away from the peninsula, creating the famous Canal de las Ballenas. Isla Ángel de la Guarda, like the adjacent coastline, is dominated by volcanic rocks related to the subduction of the Farallon Plate—mostly Miocene andesites. The massive island covers 936 km^2 (361 mi^2) and reaches 1316 m (4317 ft) in elevation. It is little explored, although the indefatigable naturalist Doug Peacock has hiked much of it. Native American artifacts have been found on the island, and there was a short-lived scallop fishery there in the 1970s. Isla Ángel de la Guarda was also a source for obsidian for early indigenous people and was carried to the Baja California Peninsula (see Bowen 2015 for summary).

But the most special thing about Isla Ángel de la Guarda is the two small coastal lagoons in its southeastern corner. It was here that intreped Baja explorer and geologist Markes Johnson made one of the most exciting discoveries possible for a naturalist—living stromatolites.

Cape Region of the Baja California Peninsula (NASA image)

Stromatolites are pancake-stacked sheets of filamentous cyanobacteria, layered with mud and sand, that were known as some of the oldest biological fossils on earth (dating to 3.8 billion years ago) long before they were discovered to be living anywhere. We now know that they occur, uncommonly, in hypersaline, herbivore-free environments around the world. The most famous living stromatolite colonies may be those in Shark Bay, Western Australia. But living stromatolites also occur at two places on the Baja Peninsula, Guerrero Negro and Marmona Lagoons (on the Pacific coast), as well as on Ángel de la Guarda Island. Much of the eastern coastline of Angel de la Guarda is scattered with coastal saltwater lagoons, and it is possible that stromatolites occur in some others along this largely unexplored coast. Markes Johnson has also documented Pleistocene stromatolites in a former lagoon at Punta Chivato (Johnson et al. 2012). And, stromatolites have long been known from Cuatro Ciénegas, in Coahuila State, a threatened habitat.

Some Gulf islands are actually part of the mainland, separated by sea barriers only since the rise of sea level at 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 1222 km^2, Tiburón is the largest island in North America south of Canada).

The Colorado River

The elevated 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 records of the great Paleozoic and Mesozoic seaways that engulfed much of interior North America. The uplift of the Plateau was a major event in the creation of the present landscape of the southwestern United States. And, the Colorado Plateau is the only large piece of the landscape that somehow did not fall subject to the torturous mountain-building events of the Laramide and Basin and Range orogenies. The timing of the Plateau's uplift, from sea level to nearly 2415 m (8000 ft), 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 or more—and tied somehow to the Laramide-age shallow subduction of the Farallon Plate. (Endnote 8)

Current thinking is that the Colorado River's present flow direction (toward the Salton Trough) was engineered by the tectonic collapse of pre-rift highlands (the Mogollon Highlands) during middle Tertiary extension in the Basin and Range Province and creation of fault-bounded basins ~6 million years ago—that is, ultimately linked to the same events that opened the Gulf of California. The Salton Trough subsided deeply and rapidly from the late Miocene to early Pleistocene, and today the trough is 10-12 km deep. In the Altar Basin, Pliocene-Pleistocene sediments containing Cretaceous forams derived from the Colorado Plateau have an average thickness of 4 km, speaking to a lengthy period of river flow in this area.

In any case, the topography of the *modern* Colorado River began with the Basin and Range faulting period, and by ~8 Ma the Basin and Range landscape of the Southwest was basically established, setting the stage for the development of the Colorado River as we know it today. Thus, by the middle Pliocene the Colorado River had achieved roughly its present-day course and begun depositing its 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 Ma, 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 Ma, the head of the Gulf of California was probably somewhere near the cities of Blyth and Parker. The delta's modern configuration was achieved during the Holocene as a result of sea level rise and tectonism.

As deposited sediments built the delta, it progressed southward along the Salton Trough. This progression can be traced in the Bouse Formation record and in the stratigraphic record. Today, the southernmost limit of the delta, and the only place brackish seawater might be found, is north of the large sediment barrier island, Isla Montague.

Due to changes in the Colorado River's course, the modern Salton Trough has been flooded by river flow many times over the past 7000 years, most recently in 1905-1906 due to human actions that created the modern Salton Sea (Ives 1858, 1861, Ortlieb 1987, Brusca et al. 2017) (Endnote 9). The old Colorado River sediments contain reworked 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 (9843 ft) of Pleistocene deltaic and marine sediments point to a long-term, mainly tectonic subsidence of the delta region, while an elevation (sill) of about 3.7 m (12 feet) is all that separates the Salton Trough from the Gulf of California.

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 may have flowed along, or 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. During the last inter-glacial epoch of the Late Pleistocene (~125,000 yeara ago) the sea level was much higher than today.

Although river sediments have dispersed into the Upper Gulf, the southern limit of the delta is Isla Montague (~31°39' N) (Davis et al. 1990, Rojas-Bracho 2018, 2019). The Upper Gulf of California should not be considered part of the delta and since the end of the last glacial period (~10,000 ybp) has probably never been estuarine in nature (i.e., salinity below 30 ppt) (Rojas-Bracho et al. 2018, 2019).

Today, the Colorado River runs a course approximately 2300 km (1430 mi) long, from the Rocky Mountains to the Gulf. The delta wetlands, now largely destroyed by lack of river flow (due to dams and diversions in the United States), is one of the harshest environments in North America, with an average annual rainfall of just 6.8 cm (2.7 in) and land surface temperatures ranging from as low as ~3º C in the winter to ~40º C in the summer.

There are no pre-1935 (pre-dam) data recording Colorado River flow across the U.S.-Mexico border and into the Upper Gulf of California. The nearest measurements are gauges on the river at Yuma, with flow data collected since at least 1894. Although there is large year-to-year variability—very dry years, and very wet, ususally El Niño years—historical records and tree-ring studies suggest the long term average annual river flow at Yuma was ~13-15 X 10^9 m^3. The amount of water reaching the Upper Gulf was significantly less than this. Thus, the river pales in comparison to larger American rivers. For example, the Mississippi River discharges 554 X 10^9 m^3 annually to the Atlantic, and the Columbia and Fraser Rivers discharge 236 X 10^9 m^3 and 110 X 10^9 m^3 annually to the Pacific, respectively.

An elegant study by Lavín and Sánchez (1999) measured the effects of the large 1993 flood release on the Upper Gulf (building from the strong 1991-1992 El Niño years). This was at a time when the delta had become highly channelized, so virtually all the water went staight to the Gulf. Even in this high-flow situation, the dilution effect on the Upper Gulf's waters was minimal, never showing signs of brackish water (<30 parts per thousand/ppt) south of Montague Island. Salinity decreased from 35.4 to 32.0 parts per thousand for a few weeks, and the effect extended only along the uppermost western shore of the Gulf from Montague Island (the beginning of the delta) to San Felipe. The idea of the entire Upper Gulf having continuous freshwater flow and being low salinty or brackish year-round in pre-dam years is not supported by any scientific data.

Today, the river's flow into the Gulf is nearly absent altogether. Tidal-flat infaunal biodiversity is dominated today by a few dozen species of molluscs, the most abundant being the snail *Nassarius moestus*, and the clams *Tellina meropsis*, *Donax navicula*, *Chionista fluctifraga* and *C. pulicardia*, and *Tagelus affinis*, as well as the brachiopod *Glottidia palmeri* and the small sand dollar *Mellita longifissa*. (Endnote 10).

The fishing village of El Golfo de Santa Clara, just south of the Colorado River Delta (on the horizon, viewed from the north).

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 on the west, and the Altar Fault-Sierra del Rosario (~600 m in height) on the east (between the city of San Luis Río Colorado and Bahía Adaír). The Cerro Prieto Fault is an active strike-slip fault along the Pacific-North American plate boundary. It also is a transitional connection between the San Andreas Fault System to the north, and the Gulf of California 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 during 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. Although the Altar Fault was probably once the main plate boundary, fault activity shifted westward to the Cerro Prieto Fault some time during the Pliocene—the Altar Fault is no longer seismically active. Coupled with realignments in the course of the Colorado River during the Pliocene-Pleistocene, the Altar Basin is no longer part of the active delta but is instead an expanse of eolian sand dunes that comprises the northernmost extent of the Gran Desierto de Altar.

Exploratory oil wells drilled 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 an early 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 Ma, and finally (4) a Pliocene-Pleistocene mix of marine-Colorado River Delta coarse-grained, poorly consolidated sandstones covered by the cap of sand dunes.

The Lower Colorado River Basin from space (NASA image)

In contrast to the Altar Basin, Laguna Salada Basin (to the west) is an example of a tectonically-active rift basin in the southwestern Salton Trough. It is described as an active half-graben product of the trans-tensional tectonics of the Gulf of California (Contreras et al 2005). The low-lying (11 m/36 below mean sea level) Laguna Salada is separated from the Mexicali Valley by the Sierra Cucapa-Sierra El Mayor mountain range (on the east), and it is bounded by Baja's massive Sierra de Juárez mountains on the west. The Laguna Salada Fault (part of the Pacific-North America plate boundary 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. Major subsidence takes place along its eastern margin (i.e., the Laguna Salada-Cañada David Fault system)(Savage et al. 1994, Mueller and Rockwell 1995, García-Abdeslem et al. 2001, Dorsey and Martín-Barajas 1999, Martín-Barajas et al. 2001, Contreras et al 2005) Thus the basin lies on the North American-Pacific Plate boundary. The location of the fault is easily seen by surface features, such as fault scarps, faulted alluvial fans, and freshly-exposed bedrock. Visible, young alluvial deposits were probably displaced in the large 1892, 2008 and 2010 earthquakes. The basin itself is filled with 2.5–3.7 mi (4–6 km) of fill deposits, and sedimentaion began during the Pleistocene when uplift of Sierra Cucapá cut off this region from the Colorado River delta plain and the Salton Trough (Contreras et al.2005). The southern half of Laguna Salada is controlled by the Cañada David Detachment, a poorly understood, active, low-angle fault. Sections of the Cañada David Detachment have produced between two and four Holocene surface ruptures with recurrance intervals of 2000 to 5000 years, yielding offsets of 2 to 5 meters in single events (and perhaps as much as 10 m)

(Fletcher et al. 2017). Hernández-Flores et al. (2015) documented seven distinct alluvial fan surfaces in the Sierra Cucapah, five likely during arid conditions of the Holocene, and two probably during more humid times associated with the last galcial maximum of the Pleistocene.

Laguna Salada is a closed freshwater sink and evaporative basin, as is the Salton Sea. It covers an area of 900 km^2 to 1000 km^2. No one has mapped the elevation of the entire basin, but most of the region west of Sierra Cucapá is 10 to 11 m below sea level. At an average depth of 10 m, a 1000 km^2 Laguna Salada basin could hold at least 10 X 10^9 m^3 of Colorado River water (and at an average depth of 5 m, 5 X 10^9 m^3 of river water). Thus, the basin can easily most of the Colorado River's flow and, in the past, likely did. But in the past, Laguna Salada was far deeper. Today it is filled with 4-6 km of alluvial deposits (Mueller and Rockwell 1995, Martín-Barajas et al. 2001), which means in the past it was a major flood-drainage basin for the Colorado River, and it could have held far more water than the river could have ever carried to Mexico in any year. Contreras et al. (2005) correlated strata in the upper 980 m of a borehole in Laguna Salada with Milnkovitch cycles.

Greatly weathered, highly calcareous sandstone formation at Pelican Point, near Puerto Peñasco ("Rocky Point"), Sonora

The Pleistocene ecological history of the Colorado River is recorded in the fluvial sediments of the Mesa Arenosa—a region of the northern Sonora coastline uplifted due to movements along the Cerro Prieto and Punta Gorda Faults (southern extensions of the San Andreas Fault System) (Colletta and Ortlieb 1984). The uplift, combined with sea-level fluctuations, resulted a nearly-continuous series of beach cliffs between El Golfo de Santa Clara and the northern shore of Bahía Adair. Part of this uplift also exposed 500 to 2700 meter-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 of sedimentary rocks uplifted as much as 130 m, and are interspersed with erosional ravines revealing ancient delta remains.

Northwest of the fishing village of El Golfo de Santa Clara, the Cerro Prieto Fault runs along the eastern edge of the Ciénega Santa Clara. The Altar Desert, on the eastern side of the Cerro Prieto Fault, lies on the North American Plate, while the

Colorado River Delta (and Ciénega de Santa Clara) lie on the Pacific Plate. Middle Pleistocene movements along the Cerro Prieto Fault probably caused the 150 m (492 ft) uplift of Mesa Arenosa (in the Mexicali Valley), which in turn caused a westward deflection of the Colorado River. Kinsland (1989) suggested the interesting idea that the Colorado Rvier once may have emptied into the Gulf of California at Bahía Adair, but strong evidence in favor of the idea has not been forthcoming.

The El Golfo Badlands cover 160 km^2 (62 mi^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 Ma reveal an ancient riparian and adjacent upland ecological history. More than 40 species of vertebrates have been found in these fossil deposits, including many tropical species and temperate species, and many species that are now extinct (Shaw 1981, 1990, Lindsay 1984). All were freshwater/riparian or terrestrial upland forms. Among these are four species of New World horses, three camels, a mammoth, giant tortoise, porcupine, 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 artesian 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

The Sierra Pinacate, Gran Desierto, and Bahía Adair (Sonora). Photo taken with 70 mm camera (Ektachrome) on board the Apollo 6 spacecraft, ~138 miles from Earth (April 1968). Courtesy of Jim Gutmann.

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.

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, Salina Grande 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 Ciénega Santa Clara, a~6000 ha wetland supported by agricultural drain water from Arizona and Mexico. South of the Ciénega is the Santa Clara Sough, a 26,000 ha basin that is inundated by sea water during high spring tides in the Upper Gulf

The source of water upwelling in the pozos is a shallow aquifer probably originating from three sources: (1) a shallow water table orginating on the Colorado River Delta (a mix of Colorado and Gila River water; Hector Zamora, pers. comm.); (2) water carried in the crustal fracture of the Altar Fault (that runs from Bahía Adaír to the Colorado River, on the Delta); and (3) rainfall in the Gran Desierto.

El Doctor springs at ground level, a few miles north of the fishing village of El Golfo de Santa Clara

The Gran Desierto de Altar

To the east of the delta/upper Gulf region is the Gran Desierto de Altar, a Pleistocene sand sea that covers 5700 km^2 (2200 mi^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 (656 ft) in height. The dunes are frequently stabilized by various shrubs, such as joint-fir/Mormon tea (*Ephedra trifurcata*) and galleta grass (*Hilaria rigida*) (Ezcurra et al. 1987, Felger 1980).

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 (3) alluvial sands from the erosion of the granitic mountains in the region (Merriam 1969, Ives 1959, Lancaster et al. 1987). 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 primary origin in eroded sands from the Colorado River, whereas the more southern dunes (in Sonora) are high in 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 Colorado Plateau, the Grand Canyon, the Colorado River and its delta, and beaches of the Upper Gulf. 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 direction of the prevailing wind (Endnote 12). Thompson (1968) estimated that, between 1926 and 1934, 184 X 10^6 tons of sediment were annually carried by the Colorado River to Yuma (about one third sand and two-thirds sild and clay).

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. Although sea levels in the Gulf have been more-or-less stable for the last 6000 years, they were as much as 130 m (425 ft) lower during Pleistocene glacial times (Endnote 13).

In contrast to the eolian dunes of the Gran Desierto de Altar, the coastal dune fields along Baja California's eastern margin are composed mainly of calcium carbonate ($CaCO_3$) derived from crushed shells of molluscs and other marine organisms. The coastal dunes of the western shores of Baja are different still, being composed mainly of inorganic materials dominated by quartz grains (silica: SiO_2) and feldspar—similar to the typical Pacific beach sand dunes of California and north to Canada.

Aerial view of El Doctor freshwater springs (pozos)

Shell midden, Estero El Soldado, near San Carlos, Sonora

The Upper Gulf of California

The Upper Gulf is characterized by a coastline with many shallow, hypersaline lagoons, called *esteros* in Mexico. Both active and extinct esteros exist, the latter represented by low, flat-bottomed "salt pans" located just inland from the coast. In Mexico, these dalt pans are usually called *playas*, but they are also known as *sabkhas*, a transliteration of the Arabic word for "salt flat."

The active esteros of the upper Gulf empty almost completely with each low tide. Although common on the Sonoran coast, esteros are uncommon on the Upper Gulf coast of the Baja Peninsula, especially south of San Felipe, due to the greater steepness of this more mountainous coastline. With an average rainfall of only around 2 inches, the San Felipe area is the driest part of the peninsula, except for the delta itself.

Shell midden, Isla Espíritu Santo, southern Gulf

The extreme tides of the Upper Gulf, combined with the gently sloping coastal plane and offshore regions, create extensive tidal flats where up to several 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 ~50 km (~30 mi) farther offshore than today. Many of the coastal salt pans, or *playas*, including some that are still inundated by the highest spring 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 in the past. Salt once mined at Salina Grande was loaded onto railroad cars at the Lopez Collada stop. (Endnote 14).

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 (*Prosopis pubscens*), bulrush (*Scirpus*), yerba-mansa (*Anemopsis californica*), and other species. Many of the salt pans fill with rainwater and become short-lived shallow "lakes," mainly in the summer monsoon season. Davis et al. (1990) noted that, "from the air, it is clear that the springs are aligned along faults that border the Salina Grance Basin on either side." The water is often red in color due to halophilic archaeobacteria such as *Halobacterium*, or the reddish-colored green alga *Dunaliella salina*. Overall, the water quality in these pozos varies from place to place and from season to season (Ezcurra et al. 1988).

Some of the ancient salt pans around Bahía Adair are now largely or fully disconnected from the sea as interdunal playa lakes, sometimes referred to as sabkhas (Glennie 1970, Handford 1982). When standing water occurs in these salt pans, from rain, local groundwater, or infiltrated sea water during the highest spring tides, the total dissolved solids (TDS) concentrations can exceed 400,000 ppm. This leads to formation of evaporite minerals, such as trona and schaireite (Lock et al. 1988, 1989). The evaporites of "Steve's Salina" have an unmistable non-marine signature, while those of "La Gaviota Salina" have a marine character (in additoin to trona and other continental-type evaporites) (Lock et al. 1990).

From northern Bahía Adaír to Desemboque de los Seris (aka Desemboque del Río San Ignacio) and Punta Tepopa on the Sonoran coast, there are intertidal outcrops of beachrock that support this highly diverse rocky-shore flora and fauna. In geological terms, beachrock is defined as "lithified littoral sediments," and it is most common in arid regions of the world (such as the Northern Gulf). In some areas, such as the Florida coast, it is composed primarily of sand. But in the Northern Gulf it forms a composite of 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 seawater and from the dissolving shells themselves. More-or-less continuous coquina outcrops have been traced to about 13 km east of Puerto Peñasco, in the shallow subtidal region or partially buried under intertidal sands. Some of the outcrops east of Puerto Peñasco include boulders more than a meter in diameter. Littoral outcrops of coquina also occur at Punta Borrascosa/Punta Gorda, and can be found discontinuously all along the coast of Bahía Adair.

Paleontologists have assigned a Pleistocene age to the Upper Gulf coquina*s*, and uranium-thorium dating has estimated an age of ~130,000 ybp, supporting this age assignment (Hertlein and Emerson 1956, Davis et al. 1990). Ortlieb (1979, 1991) correlated the beachrock in the upper intertidal at Bahía la Cholla to the 120,000 ybp sea level high stand (last interglacial). One form of coquina is notably high in *Chione* clam shells (the "*Chione* coquina") and is considered an index bed, and today *Chione* coquina occurs at an elevation of 5-23 m above mean sea level between Punta Borrascosa/Punta Gorda and Estero la Pinta. The Punta Gorda fault, a major dextral strike-slip fault, is responsible for the 18 m elevation of the sea cliffs along the shore at Punta Borrascosa/Punta Gorda (Colletta and Ortlieb 1984). Ancient, higher than present sea levels are also indicated by subsurface coquina beachrock located beneath sand dunes several hundred meters inland from Estero de Morúa (DeCook et al. 1980), some of which was measured to be 24 m thick.

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 one of its larger freshwater springs (pozos)

Freshwater pozos create "islands" of riparain flora in the salty Salina Grande

Salina Grande; a large expanse of crystallized salt

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 (75 ft) above mean sea level (his "*Chione cancellata* shoreline), and the third at 60–90 m (33-40 ft) 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 MIS 5e shoreline.

Thirty miles southeast of El Golfo de Santa Clara, at the headland of Punta Borrascosa/Punta Gorda, an ancient elevated 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 *Chionopsis gnidia*, documenting the last Pleistocene interglacial (~125,000 ybp) seafloor habitat.

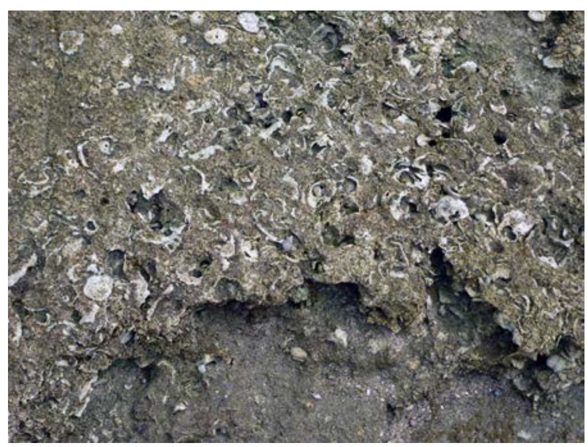
Fossil sand dollars from a Pleistocene coastal outcrop at Punta Borascosa: *Encope grandis* (left), *Encope micropora* var. *borealis* (right)

One of the many salinas in Bahía Adaír, which are often innundated with sea water during high spring tides, refreshing their salt content

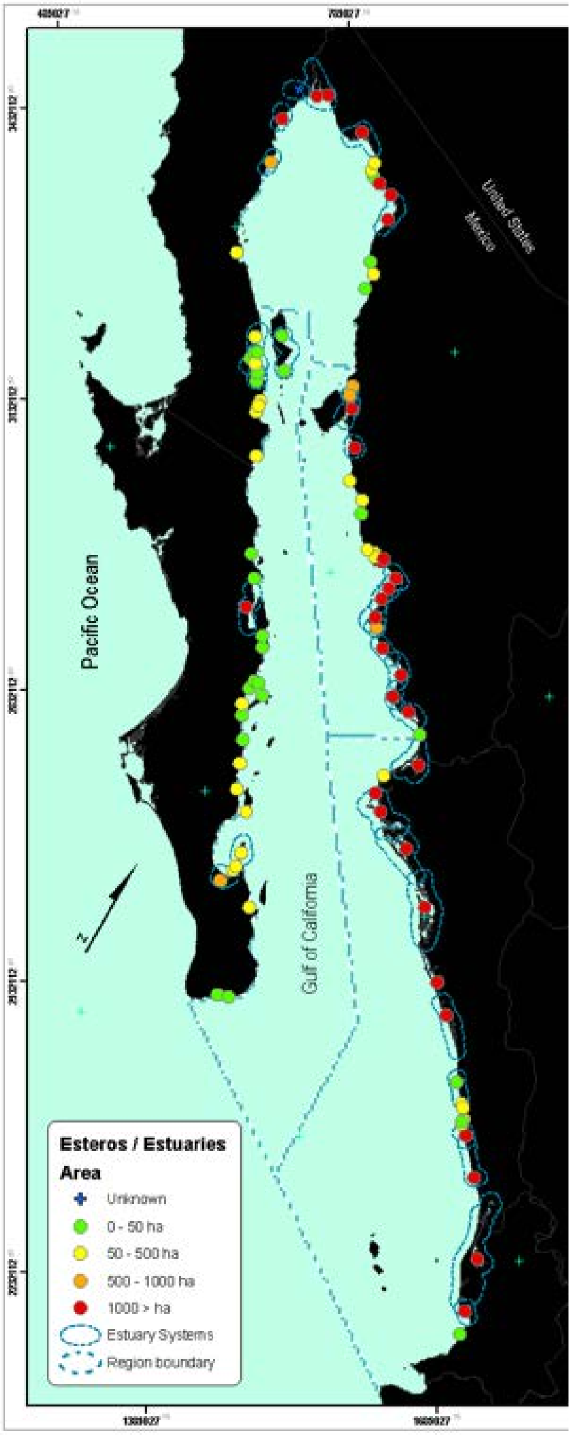
Fossil bed (probably Late Pleistocene) on Isla Tiburón, with bivalve shells and slender calcareous tubes (probably polychaetes) (Photo by Cathy Marlett)

Estero el Soldado, a mangrove lagoon near Guaymas-San Carlos, Sonora

Coquina beachrock near Desemboque de los Seris, Sonora (Photo by Cathy Marlett)



Coquina beachrock, Punta Pelicano, near Puerto Peñasco, Sonora



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.

Coquina beachrock, Punta Borascosa, ~10 mi south of El Golfo de Santa Clara, Sonora

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 (University of Arizona)

The Gran Desierto and El Pinacate mountain range (the Sierra Pinacate) comprise a UNESCO and Mexicodesignated Biosphere Reserve, as well as a U.N. World Heritage Site (the latter 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 active Cerro Prieto Fault, so are part of the North American Plate.

The Sierra Pinacate, from the dunes of the Gran Desierto de Altar

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 Ma, and the delta had reached the Yuma area by ~4 Ma. 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.

The Pinacate Biosphere Reserve. The Sierra Blanca stands watch over the massive Ives Lava Flow with spring booms of brittlebush and creosote

The Sierra Pinacate began as Volcán Santa Clara, a single shield volcano that expanded in size with successive eruptions from a central vent complex 1.7 to 1.1 Ma, based on potassium-argon (K/Ar) dating of the shield lava (although some geologists suggest the shield volcano could have originated 3–4 Ma). 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 exquisite 1.6 km-diameter Elegante Maar Crater has been dated at 16,000 to 20,000 ybp, or 32,000 ybp (+/- 6000 years) using Ar-Ar methods (an earlier estimated date of ~460,000 ybp turned out to be in correct and was based on K/Ar dating methods which are not reliable for basalts less than ~100 thousand years in age).

The youngest of the lava flows in the Pinacate region probably took place just 8000 to 16,000 years ago, which opens the possibility that early Native Americans could have witnessed them! The youngest dated flows are the La Laja flow, dated at 12,000 ybp (±4000 years) and the Ives Flow (13,000 ybp, ±3000 years). The oldest dated lava flow is the Carnegie Cone Flow, dated at 38,000 ybp (±8000 years). The largest lava flow visible today is the Ives Flow, which covers more than 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 del Rosario are the only ranges within the Pinacate Biosphere Reserve that are not part of the volcanic history of El Pinacate—they formed during earlier Basin and Range tectonic activity (the Sierra del 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 del Rosario stand out in contrast to the surrounding dark volcanic ranges. Almost no Paleozoic rocks are known to crop out in the Gran Desierto.

Much of the Ives Flow comprises a maze of lava tubes, ranging in diameter from 10 cm to 10 m (4 in to 35 ft). Lava tubes occur in other flows in the Pinacates, but nowhere are they so abundant as in the Ives Flow. Roughly two-thirds of way from the start of the Ives Flow (on the flanks of the Sierra Pinacate) toward the Sierra Blanca is a large region of collapsed lava tubes, where the pahoehoe flows broke apart to leave tile-like staking of the lava rock (see photo). Some of these tubes are 10 m in diameter, and many host large colonies of bats. Geologist Dan Lynch has suggested that the collapse region resulted from the bursting of one or more large, deep gas bubbles rising up from far below. Lynch named the Ives Flow after Ronald L. Ives, one of the most important scientific explorers to work in the region. The basalt of the Ives flow differs from most of the rest of the Pinacates lava in being derived from a hotter and longer magma formation process, creating a type of lava known as tholeite. Tholeite is typical of oceanic island volcanoes, such as seen in Hawaii, and also of spreading centers on mid-ocean ridges (such as on the seafloor in the Gulf of California). Tholeite is typically rich in aluminum and low in potassium. Like other flows in the region (and around the world), the surface texture of these basalts are common referred to as aa and pahoehoe, names originating in the Hawaiian language. Aa is rough and angular, with a great deal of trapped gas that can give it a frothy texture. Pahoehoe is more laminar and smooth, or ropy, with far less trapped gas.

Collapsed lava tube in Ives Flow, with fractured tiles of pahoehoe lava

The southernmost, undated vent in the Pinacate Biosphere Reserve does not yet have a published name, although Pinacate specialist Dan Lynch has calls it “Escalante,” and it originates on the north side of Sierra Blanca (see photo). Its flow wraps around the Sierra to join the massive Ives Flow. Also scattered within the Ives flow are isolated hills and older smaller lava cones that are completely surrounded by the Ives lava flow. These stand out like islands in a black sea, and such lava-surrounded older formations are known as kipuka (a Hawaiian word).

The Escalante Flow. With its vent on the north side of Sierra Blanca, this dark black flow wraps around to join with the huge Ives Flow on the south side of the range. Pinacate Biosphere Reserve

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 (8840 m/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 5,840m (19,160 ft), giving it an actual height of just 3,010 m (9,875 ft). The tallest mountain on Earth is Mauna Kea, which rises from a depth of 5486/18,000 ft m (on the seafloor) to 3962 m/13,796 ft above sea level, a total height of 9,758 m/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 close 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 Gulf of California Rift Zone, as some have suggested).

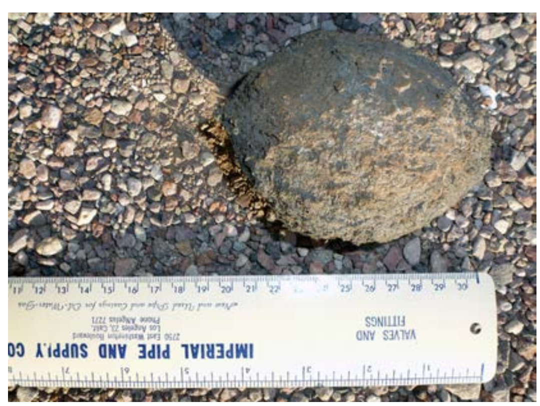
A small lava tube in the Ives Flow, Pinacate Biosphere Reserve

…..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 about 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 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. Some of the explosive craters generated giant lava bombs that spun into spheroidal shapes in the air as they cooled; these volcanic bombs, some as large as small cars, can be seen all through the Pinacates.

Ropy pahoehoe lava of the Ives Flow, Pinacate Biosphere Reserve

Many of the small rocks and pebbles in the Pinacate Reserve have a varnishlike sheen, a very thin, shiny, light or dark patina. This "desert varnish" is actually a byproduct of biogenic activity involving the interaction of iron and manganese with clay-bearing dusts and bacteria. The iron/manganese coating is notably high in nickel that may originate from micro-meteoritic dust that continually enters the Earth's atmosphere and settles on everything in the environment. The thin layers of dust and oxides develop very slowly, probably over tens of thousands of years.

Pinacate researcher Dr. Dan Lynch, with very large volcanic bomb near Tecolote Cone



A small volcanic bomb, sitting on top of desert pavement in the Pinacates

The desert floor in the Pinacates is often covered with small, tightly placed stones, creating a cobblestone or pavementlike effect on top of the soil. The stones are often coated with desert varnish. These "desert pavements" occur in extremely arid landscapes around the world, and they typically lie atop fine-grained soil composed of wind-blown dust called loess. Loess soils are common in the volcanic region of the Pinacate Biosphere Reserve. The origin of desert pavement is still not well understood, but it might be the result of decades of little surface water flow/disturbance and a near-absence of plant and rodent disturbance, allowing winds to continually remove the loess over millennia.

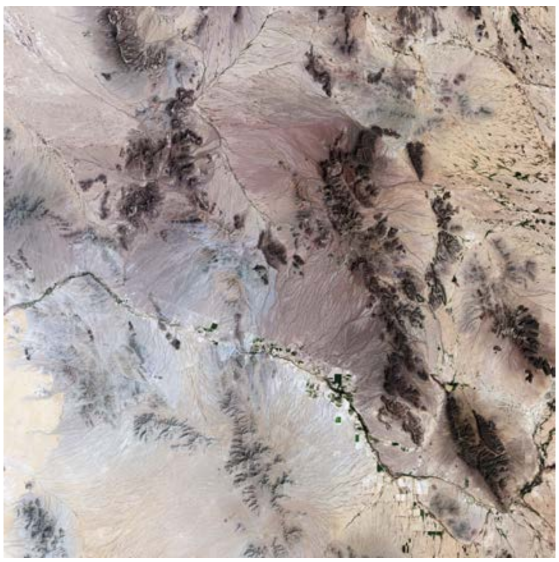
Desert pavement in the Pinacates, each stone being coated with desert varnish (including the larger rock sitting on top of the "pavement")

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 in the Pinacate Biosphere Reserve: 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.

Burrowing animals, such as these harvester ants, can disrupt desert pavement

Batamote Hills, Pinacates

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—although its water flows reaching the Gulf have been rare in the last 100 years and associated only with high intensity precipitation events (e.g., tropical hurricanes). Although there are no direct data supporting a past history of perennial flow for the Río Sonoya to the coast over the past 6000 years, long-term flows to the Estero de Morúa-Estero La Pinta coastal lagoon complex might have occurred during the 4,510 – 3,250 ybp (2,500 – 750 B.C.) interval of increased moisture in the Southwest. There has likely always been perennial subsurface flow, and this still



August 2016 Landsat 8 image showing all of Organ Pipe National Monument and, just south of the monument's border (and the U.S. border), the Río Sonoyta. The small town of Sonoyta is also visible along the river's course. Not shown is Pinacates, where the river is deflected to the south.

exists today from the large Río Sonoyta aquifer. This estero complex—which could be less than one million years old—began being visited by Native Americans at least four-thousand years ago, and probably earlier. Today, the Río Sonoyta's subsurface flow runs to Estero La Pinta (visible in vegetation patterns of satellite images) just east of Estero de Morúa on the coastline near Puerto Peñasco. And, as recently as the early 1970s the river frequently had long-lasting surface flow years as far south as the Batamote Hills.

However, the aquatic ecosystem of the Río Sonoyta is disappearing, due to drought and groundwater over-draft, and its native species are threatened by introduced species. The "headwaters" of Río Sonoyta are primarily on the east and west slopes of the Ajo Mountains and adjacent valleys, including the drying Sonoyta Valley. The springs at Quitobaquito, and much of the river west of the town of Sonoyta, have long been fed by subsurface runoff from the La Abra Plain (in Organ Pipe National Monument). In normal years, the only surface water flow in the river is now an intermittent segment (locally known as Agua Dulce) about one kilometer in length, just south of Organ Pipe Cactus National Monument. In this last little trickle of water live two important native fishes, the endangered Sonoyta pupfish (*Cyprinodon eremus*) and the indigenous longfin dace (*Agosia chrysogasster*), although the later might now be extirpated. Invasive introduced fishes include mosquitofish (*Gambusia affinis*), black bullhead (*Amerius melas*), and Gila topminnow (*Poeciliopsis occidentialis*).

The formation of the Sierra Pinacate that disconnected the Río Sonoyta from the Colorado River Delta has been proposed as a vicariant event that led to disjunct populations of aquatic species such as the Río Sonoyta (=Quitobaquito) and perhaps the Lower Colorado River desert pupfishes

(*Cyprinodon eremus* and *Cyprinodon macularius*), as well as populations of longfin dace (*Agosia chrysogaster*), and Sonoran mud turtle (*Kinosternon sonoriense longifemorale*). Longfin dace and mud turtles are rare or absent in the Delta area today due to drying from overextraction of Colorado River water. Molecular dating places the age of separation of the two pupfish species at roughly the same age as the formation of the Sierra Pinacate, ~1.3 Ma.

Many natural water tanks, or tinajas, occur in the Pinacate Biosphere Reserve. These rock depressions hold rainwater for many

Tecolote Crater, Pinacate Biosphere Reserve

One of several lava flows from the sides of the Tecolote Crater, Pinacate Biosphere Reserve

months and provided valuable sources of drinking water for Native Americans in the past, and important archeological materials are associated with virtually all of them. They are also watering holes for the large mammals of the region, including coyote, foxes, bobcat, mountain lion, striped and spotted skunks, badgers, ringtails, raccoons, javelina, mule deer, white-tailed deer, pronghorn, and bighorn sheep.

Cerro Colorado Crater, Pinacate Biosphere Reserve

Rocks That Tell Stories

Given our understanding of the geological history of northwestern Mexico, the exposed coastal rocks around the Gulf of California now reveal their origins and provide us with glimpses into the past. Most rocks along the Gulf's coastline belong to one of three main types: (1) extrusive igneous rocks, such as basalt, andesite, rhyolite, and tuff (consolidated volcanic ash); (2) intrusive

Elegante Crater, Pinacate Biosphere Reserve

La Laja cone and lava flow, Pinacate Biosphere Reserve

Two photographs of the Ives lava flow, with the Sierra Blanca in background, Pinacate Biosphere Reserve

igneous rocks like granite, dactite, granodiorite, and diorite; and (3) sedimentary rocks such as limestones (“white rocks”), sandstone, and beachrock. Metamorphic rocks are rare along Gulf shorelines. In the Gulf region, classification is strongly correlated with geologic age, so recognizing rock types along the shore quickly sheds light on the geological history of the area.

Tinaja I’itoi is one of the largest and most archeologically interesting tinajas in the Pinacates

Along Gulf shores, intrusive igneous rocks such as tonalite, granite and diorite are the oldest rocks encountered. They formed deep in the Earth and were later uplifted by tectonic action and exposed by

Native American rock circles (sometimes called “sleeping circles”) are often found near freshwater sources in the Pinacate Biosphere Reserve

Native American cooking utensils, such as this gyratory grinder, are often found near tinajas in the Pinacate Biosphere Reserve

erosion. Exposed Cretaceous granite can be seen all along the Baja California Peninsula, from San Diego to the mountains west of Loreto (the Sierra La Giganta) and on to the famous sea arches of Cabo San Lucas, at the tip of the Peninsula. Even the spectacular weathered boulders of the Cataviña area are of this same Cretaceous granite. The granitic rocks of the tilted 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 peninsula is clearly underpinned by numerous massive granitic batholiths (some authors refer to the sum of these emplacements as the "Peninsular Batholith"). Related batholiths, broadly generated around the same time, underpin the Transverse Ranges and Sierra Nevada of California. In contrast, the well-known rocky point called Punta Pelícano, near Puerto Peñasco, Sonora, is 80–100 million-year-old granodiorite (Anderson and Silver 1974) (Endnote 15).

Andesites and the other extrusive (surface-formed) volcanic rocks date from the Miocene or younger, and are largely products of the subduction of the Farallon Plate beneath North America or the extensional tectonics of the Basin and Range Province. Andesites, rhyolites, and basalts in the Gulf formed throughout most of the Miocene, deposited as volcanic surface flows. The andesites, rhyolites and dacites of northwestern Mexico are often 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's mainland coastlines and in nearshore eroded canyons. These layers were faulted and exposed during the tectonic events related to the rifting of the Baja California Peninsula from the mainland, and many of the coastal cliffs of the Baja California Peninsula are composed of andesite. One of the best places to observe the products of this Miocene volcanism is in the extraordinary Sierra Aguaje, at San Carlos, Sonora. This entire range is highly fractured, with abundant tuffs, resulting in a landmass that absorbs rainfall like a sponge (hence the name, *Aguaje*) and then releases it slowly in hundreds of small perrenial springs and seeps.

The dominant coastal rock type found on the islands of the Gulf is andesite, although some granitic islands (e.g. Isla 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. This is due to the westward tilting of the island that has exposed the older intrusive rocks along its eastern shore.

Andesites and rhyolites are igneous rocks formed from surface flows, whereas granite is an igneous rock formed in place, 1-8 miles deep underground, often forming large batholiths [Endnote 16]. Andesites and rhyolites are common on the mainland, due to the volcanic activity associated with the submergence of the Farallon Plate and its volcanic arc. These surface-formed igneous rocks are less common on the Baja

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

Sierra Blanca, Pinacate Region, is one of the western-most Basin and Range mountains in North America

Peninsula, where uplifted granites predominate as exposed plutons or batholiths. However, they do blanket the southern San Pedro Mártir and much of the Sierra Gigante (west of Loreto).

Biogenic marine carbonate rocks (usually limestone, $CaCO_3$) are commonly the youngest rocks in the Gulf region. They 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 Ma. Sea-level retreats and tectonic uplift have subsequently exposed these ancient marine beds. Limestone deposits can form from benthic accumlations of plankton skeletons (e.g., coccolithophores, foraminiferans), 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 high sea-level stands of the Pliocene, some of the large islands—including San José, Monserrat, Carmen, Ángel de la Guarda, and Cerralvo— 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.

Namesake for the region, the Pinacate beetle, *Eleodes armata*, is a common tenebrionid in the area

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. Large Pliocene limestone deposits also occur on Isla Monserrat and at the base of Bahía Concepción. These white limestone fossil Pliocene bays and lagoons can be seen from the air during commercial flights down the peninsula. 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 modern-day coralline-sand beaches on Isla Coronados, suggesting a change in beach environments since late Pleistocene time. 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 an ancient igneous plug from the eroded chamber of a former volcano. A 75 m-long fossil bed of silica carbonate (possibly formed by stromatolites) has been described from Bahía Concepción.

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

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 Pulmo (23º 30' N, 109º 30' W), although small patch reefs can be found in Bahía San Gabriel on Isla Espíritu Santo.

It has been noted that the reef tracks at Cabo Pulmo are not built soley by framebuilding organisms, or solely upon a coral and coralline base. Instead, they arise from intrusive volcanic dikes, thus some would consider the it (at least sedimentologically) to function only in a limited way as a coral reef (e.g., Riegl et al 2007). Biologically, however, the reefs at Cabo Pulmo fuction as a coral reef (e.g., Brusca and Thomson 1977; Reyes-Bonilla 2003).

Land's End–Cabo San Lucas, a Cretaceous granite sea arch at the southern tip of the Baja California Peninsula

The Gulf's modern coral fauna is mostly derived from the western Pacific, the original Caribbean-shared coral fauna having largely gone extinct subsequent to the closure of the Panamanian Seaway around 2.6 Ma (a recent proposal that the seaway is 15 million years old seems unlikely). 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 Ma) 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.

Miocene red rhyolite rocks embedded in yellowish tuff, Nacapule Canyon (San Carlos), Sierra Aguaje, Sonora

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 crustal material from below, a process that occurs on both oceanic and continental plates (divergent, or "constructive" plate margins). Thus rifts are places where new plate material forms. For example, the Great African Rift Valley in eastern Africa is a location of active continental rifting and volcanic activity. When two plates converge, the denser plate tends to subduct—or thrust—beneath the less dense plate. Oceanic plates are denser than continental plates, and consequently they subduct beneath continental plates. For example, the Pacific Plate is subducting beneath continental Asia near Japan (a convergent, or "destructive" plate margins); the associated active volcanism has formed the Japanese islands. Because of the process of plate subduction, the life of Earth's crust is finite and the processes of plate tectonics has returned most of the crust back into the Earth's interior. Very few regions of ancient crust remain, but one is the Hudson Bay terrain of northeastern Canada, which is mainly composed of 2.7-billion-year-old Neoarchean felsic crust.

In addition to constructive and destructive plate margins, 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 ("conservative plate margins"). The San Andreas-Gulf of California Fault System represents such a boundary between the Pacific and North American Plates, where these massive plates incrementally shear past one another in a long series of strike-slip and transform faults. At all plate boundary types, the plates sometimes temporarily "stick" along the faults. Such transform faults become sites of huge stresses in the Earth's crust. Earthquakes occur when the forces of relative plate motion overcome this friction and the respective plates jolt into new positions. Earthquake epicenters are commonly used to map the location of such faults, especially in the subsurface.

ENDNOTE 2. 40-20 Ma, the subduction of the Farallon Plate caused an episode of intense volcanism north of Mexico that covered much of the future 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. Marine-derived sedimentary deposits occur along both coasts of the Baja California Peninsula, as well as on mainland Mexico and in southern California, and when these strata can be dated they provide clues to past oceanic incursions before the separation of the peninsula from the mainland. However, it is important to understand that such evidence for incursions does not always require the presence of a large Gulf or formation a seaway across the Baja Peninsula. Documentation of marine sedimentary deposits can simply be evidence of a local embayment of the Pacific Ocean. The marine sedimentary record can be summarized as follows.

During the early Miocene (~22 Ma) transform motion between the Pacific and North American Plates caused subsidence in the continental borderland of northwestern Mexico. This subsidence coincided with a global rise in sea level—two factors that can work together to create marine transgressions (i.e., oceanic seaways and embayments over continental coastal regions). Sedimentary evidence of an early Miocene marine transgression is found along the western edge of northern Baja California today.

During the middle Miocene (~12 Ma), land subsidence related to Proto-Gulf extension began, and marine transgressions or embayments from the west coast of Mexico might have occurred then. It has been suggested that such embayments left behind some of the oldest traces of marine sedimentary rocks now exposed within the Gulf of California. However, the nature of the known middle Miocene marine microfossils is debated and there is strong argument that they are reworked materials and not in situ deposits. It is unclear where such transgressions might have occurred, but plate tectonic reconstructions suggest the only possible entries could have been through two low topographic passes south of modern-day Sierra San Pedro Mártir and north of Los Cabos. But, there are no marine deposits on the peninsula that support these proposed embayments. Marine strata exposed on southwest Isla Tiburón has been cited as evidence for a middle Miocene marine incursion into the Gulf of California at least 7 Ma. However, the most recent work has shown these deposits to be latest Miocene to early Pliocene in age, 6.2-4.3 Ma, and this is now viewed as the first incursion of Gulf of California waters to this region (e.g., Gastil et al. 1999, Bennett et al. 2015).

By the late Miocene (~6.5 - 7 Ma) localized rifting and extension increased subsidence of the large marine basin that is now the southern Gulf of California, connected to the Pacific Ocean through the modern-day mouth of the Gulf. In Baja California, evidence of this late Miocene southern Gulf is seen in ~7 Ma sediments of the Los Cabos area that match up with sediments at Punta Mita (near Puerto Vallarta, on the mainland). Further north, ~7 Ma marine sedimentary rocks outcrop near the town of Santa Rosalía (Holt et al. 2000), and have correlative marine deposits in the eastern Guaymas basin (Miller and Lizzaralde, 2013). Slightly later, marine waters flooded into the Northern Gulf and Salton Trough, almost doubling the length of the Gulf. These are the ~6.3 Ma marine deposits at Isla Tiburón, San Felipe (Baja California), the Altar Basin and San Gorgonio Pass. The Gulf has gradually widened over the past 6 Ma due to oblique rifting of the Baja Peninsula away from mainland Mexico. Some workers have suggested that the main opening of the Gulf might have preceded the separation of the tip of the peninsula, which detached a bit later in time (~5 Ma), only to “catch up” with the rest of the peninsula and attach itself; however, there is no geological evidence in support of this idea.

Helenes and Carreño (1999) proposed a location for a mid-peninsular seaway that roughly corresponds to the latitude of Laguna San Ignacio on the west and Santa Rosalía to the east (this is one of the lowest-elevation stretches of the peninsula, north of La Paz, today). It might have been through this route, they suggest, that a 12-13 Ma old marine transgressions, or seaways/embayments entered from the Pacific Ocean prior to rifting of the Baja Peninsula from Mexico.

The course of the Colorado River below Grand Wash and the site of Hoover Dam was established post-6 Ma and pre-4.8 to 4.3 Ma (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, allowing drainage from the Rocky Mountains to reach the Gulf of California and beginning the sediment supply and growth rate of its delta.

ENDNOTE 4. The eastern boundary of the Salton Trough is the southern San Andreas Fault. The western boundary 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 and connect to an extensional pull-apart basin called the Brawley Seismic Zone. This is the most northern of the long series of pull-apart basins distributed along the length of the Gulf of California. The proximity of this extension basin 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, 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 nearby Laguna Salada Basin 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 elevations that are below sea level today.

ENDNOTE 5. The Colorado River Delta (that area with alluvium deposits from the Colorado River) covers an area of 8,612 km^2 (3,325 mi^2), situated between 31° 03’ and 33° 45’ N latitude. The Colorado River is unique among the major delta-forming rivers of the world in that it has alternately discharged its waters into the sea and into land-locked basins.

The Mexican portion of the Colorado River Delta was first mapped by Derby in 1851 (Derby 1852), by Ives in 1858 (Ives 1861), and most famously by Sykes in 1907 and again in 1937, although today a variety of satellite-based images allow for accurate GIS mapping of the region (Figure 2). The most comprehensive and detailed description of the delta ever published was probably that of Godfrey Sykes (1937) for the American Geographical Society, although many present-day workers have overlooked that important volume. Sykes's description was based on 45 years of surveys in the delta, often accompanied by botanist-explorer D. T. MacDougal. His 193-page narrative, with abundant statistics, maps and photographs, provides an accurate history of Colorado River flow across the delta and the changing physiographic history of the region from 1890 to 1935 (including a blow-by-blow account of the accidental formation of the Salton Sea). By making detailed comparisons of notes and maps of the delta from previous explorers, beginning with Francisco de Ulloa in 1539, and continuing through the explorations of Joseph C. Ives, logs of steamships that once connected the Gulf to Yuma (Arizona), and border projects by the Imperial Land Company and the U.S. Government, Sykes described the dynamic history of the delta and its river channels as they changed from one decade to the next, and even from one flood event to the next.

Sykes (1937) showed that the undammed Colorado River in the delta changed course frequently, islands and shoals formed and disappeared, and various topographic lows became temporary lakes that impounded the river's flow for years at a time. From 1909 to 1930, Sykes described the river as flowing predominantly to the western side of delta, where it was deflected by the Sierra Cucapá. From there, it could run northward to the Salton Basin (via New River), southward in the Río Hardy channel to either the Laguna Salada Basin or to the sea, or it could pool in one of the large topographic lows just south the U.S.-Mexico border, such as Volcano Lake or Pescadero Basin (east of the Sierra Cucapá). Even when the main channel was on the eastern side of the delta, it could drain directly into Volcano Lake (a topographic low on the Cerro Prieto fault line) via the old Paredones River. When the river flowed northward, it threatened the towns of Calexico/Mexicali or Yuma and, in fact, it flooded those towns on more than one occasion. The two main watercourses that drained the Colorado River toward the Salton Basin were the Alamo River and the New River, whose channels still exist, although today they mainly carry irrigation drainage from croplands. Just after the turn of the 20th century, the U.S. and Mexico began building levees on the Mexican side of the border to protect Yuma and Calexico/Mexicali, the first being the Volcano Lake Levee constructed in 1908, and since then hardly a year passed without the U.S. or Mexico constructing new levees or canals on the delta.

During the 16th and 17th century explorations of Alarcón, Díaz and Kino, the mainstem of the Colorado River also flowed on the western side of the delta, probably occupying the Río Hardy channel. However, by the time of the Derby (1852) and Ives (1858) surveys, the mainstem had moved to the eastern side of the delta, and it may have maintained that position until the great floods of 1890-91, when the river again broke toward the west. During those floods, most of the river's water flowed north into the Salton Basin (Sykes 1937). Beginning in 1901, U.S. land developers opened canals directly from the river to the Imperial Valley to support a fledgling agricultural enterprise, and it was the flood-rupture of these diversions in 1905 that led to the most recent refilling of the Salton Basin (creating the Salton Sea). In more recent (post-dam) times, the river has been channeled again on the eastern side of the delta by an extensive series of dikes and levees. Over the past 75 years, most of the delta has been converted to irrigated agriculture.

Feirstein et al. (2008) estimated the volume of Colorado River deltaic sediments at approximately 41,682 km^3, but Dorsey (2010) calculated it to be 220,000 km^3–340,000 km^3. Most of these sediments lie within the Salton Trough/Basin, a topographic depression that extends over parts of southeastern California, southwestern Arizona, and northwestern Mexico, within the Sonoran Desert (Lippmann et al. 1999, Anderson et al. 2003, Crowell et al. 2013). The trough is a classic graben formation lying on the west side of the San Andreas transform fault system and was formed by active rifting along the landward extension of the East Pacific Rise. This rifting/spreading center thus lies between the Pacific and North American tectonic plates. Cartographers generally recognize the region, from north to south, as the Coachella, Imperial, and Mexicali Valleys, as well as the floodplain of the Colorado River that abuts the Upper Gulf of California. Sediments in the Salton Trough have accumulated atop a Paleozoic basement of limestone, sandstone, conglomerate, and metamorphic rocks (Gastil et al. 1992, Delgado-Granados et al. 1994, Nations and Gauna 1998, Fletcher and Munguía 2000, Johnson et al. 2003, Bialas and Buck 2009). The sediment-basement interface is irregular and occurs at depths from 1.4 to 5.6 km (Anderson et al. 2003, Lovely et al. 2006, Crowell et al. 2013, Pacheco et al. 2006). Historically, large-scale flood events on the Colorado River served to recharge the aquifer of this large contiguous hydrologic basin.

Although the Colorado River Delta includes the Salton Basin, much of the recently published hydrological research focuses only on the southern portion of the basin, from the U.S.-Mexico border south to the Upper Gulf of California—that part of the delta lying within the Mexicali Valley (e.g., Olmsted et al. 1973, Feirstein et al. 2008). Some recent workers have even constrained the "delta," for working purposes, to the area of the Colorado River between the constructed levees, plus the various wetlands—about 600 km^2 (Luecke et al. 1999, Cohen et al. 2001). The larger of these wetlands today are the Río Hardy and El Doctor wetlands, the Ciénega de Santa Clara, and Ciénega El Indio. The 36 km-stretch of the Colorado River from the Morelos Dam (at the California-Baja California border) to San Luis Río Colorado (at the Arizona-Sonora border) is considered as the uppermost extent of today's remnant Colorado River Delta in Mexico and has been called the limitrophe reach (Cohen et al. 2001, Cohen 2013). Since the 1980s, the

Colorado River channel has been bordered by high, engineered levees that prevent surface water from reaching most of the riverbed (and vice versa).

Composite satellite image map (GIS based) of the Northern Gulf of California and Colorado River Delta (copyright R.C. Brusca, 2016). The Laguna Salada Basin covers approximately 990 km^2

The delta region from the U.S.-Mexico border to the Upper Gulf lies in the Lower Colorado River Valley subdivision of the Sonoran Desert, which is one of the hottest and driest ecologicallydefined areas in North America. Davis et al. noted precipitation in the Northern Gulf to average less than 100 mm yr^{-1}, Zamora-Arroyo et al. (2013) stated that precipitation on the delta averaged about 65 mm yr^{-1}, and Cohen et al. (2001) reported it as 54 mm yr^{-1} on the delta based on IBWC data for the years 1992-1998. DeCooke et al. (1979) reported the average annual precipitation at Puerto Peñasco was 93 mm (from 1948 to 1977), and Green (1969) recorded an average annual precipitation of 73.5 mm during the drought from 1959 to 1967. Thompson (1968) and Ezcurra and Rodríguez (1986) reported average annual precipitation across the delta region as 68 mm, with evaporation rates up to 250 cm yr^{-1}. Not only is it the driest part of the Sonoran Desert, it experiences significant spatial variability in precipitation; long-term annual precipitation means from El Centro (California) average around 12.7 mm (1956-1998), from Mexicali (Baja California) average 160 mm (1973-1991), and from Yuma Valley average 11.6 mm (1987-1998) (Feirstein et al. 2008). Felger (2000) reported annual precipitation means of 55.3 mm at San Luis Río Colorado (1927-1967) and 40.2 mm at Riito (1950-1967), based on data from Hastings (1964) and Hastings and Humphrey (1969).

The Morelos Diversion Dam, on the U.S.-Mexico Border (at the town of Algodones, Baja California). River water in the foreground belongs to the U.S.; water behind the dam belongs to Mexico.

An understanding of the Colorado River Delta's overall water budget has only just begun to come into focus. Across the entire delta (on both sides of the international border), agriculture is the single largest water user, consuming nearly 50% of total river inflow, whereas natural vegetation uses about 10% of the total inflow. Urban water use accounts for about 2% of total regional water consumption, most of this being met with groundwater pumping (Cohen and Henges-Jeck 2001). However, evapotranspiration (from cropland and open-water delivery canals) accounts for the single largest consumptive use of water in the delta, removing nearly half of the total inflows during non-flood years (Cohen and Henges-Jeck 2001). Recharge associated with agriculture is the primary source of recharge to the aquifer today (Cohen and Henges-Jeck 2001). Cohen (2013) used monitoring-well data to plot water table depth along the limitrophe stretch between Morelos Dam and the Southerly International Boundary (SIB). He found that over the past 70 years the water table dropped 12 m near the SIB, and about 3 m near Morelos Dam. Depth and variability of the water table varies greatly along the limitrophe, tending to drop more quickly in response to lack of surface flow the farther downstream the measurements are taken.

Carrillo-Guerrero et al. (2013) calculated a water budget for the delta south of the border that estimated a total surface water input of 2985 million m^3 yr^{-1} combined Colorado River flow past Morelos Dam, plus rainfall (based on data from April 2004 to April 2005). The U.S. has been compliant in meeting its annual water allotment delivery to Mexico of 1.85×10^9 m^3. However, the water delivered is generally of too low quality for urban use and often too high salinity for agricultural use. In non-flood years, about 90% of the Colorado River water entering Mexico is diverted as soon as it crosses the border, at Morelos Dam, into the Canal Reforma and Canal Alamo where it is distributed via approximately 1,662 km of irrigation canals to border-region agriculture (Cohen and Henges-Jeck 2001, Cohen 2005, Feirstein et al. 2008, Carrillo-Guerrero et al. 2013).

In addition to water from the Colorado River allotment, over 700 federal and private wells in the Mexicali Valley pump subterranean water for urban and agricultural use. During non-flood years, water from wells pumping the Mexicali-San Luis Río Colorado aquifer is used to meet agricultural demands and reduce salinity levels of the water entering from the U.S. The Mexicali agricultural valley (Federal Irrigation District 014-Río Colorado) has over 200,000 ha of irrigated fields (Nagler et al. 2007, Carrillo-Guerrrero et al. 2013). The main crops are wheat, alfalfa, and cotton that, together, occupy 74% of the cultivated area and use 71% of the water available in the district (Carrillo-Guerrero et al. 2013). At least a quarter of the water delivered for agricultural use is lost from the irrigation canals alone, due to evaporation and ground seepage (Carrillo-Guerrero et al. 2013, based on CONAGUA estimates). Alfalfa is the region's most water-intensive crop, with a very high evapotranspiration rate (Erie et al. 1982, Jensen 1995).

Carrillo-Guerrero et al. (2013) estimated evapotranspiration rates from agricultural fields and freshwater/marsh wetlands in the region. They concluded that in non-flood years about 90% of the water diverted into agriculture fields in the Mexicali Valley is lost due to evapotranspiration alone (about 1.9×10^9 m^3 yr^{-1}, based on data for the 12-month period April 2004-April 2005).

This is roughly the same amount of water guaranteed by the U.S.-Mexico Colorado River water treaty, and thus the amount of surface water that typically crosses into Mexico during non-flood years. However, the calculations of Carrillo-Guerrero et al. (2013) do not include water lost by way of crop and other vegetation biomass production, nor loss of water to the system by pumping it entirely out of the Mexicali Valley (e.g., water supplies to Tecate, Tijuana, etc.).

Carrillo-Guerrero et al. (2013) note that seepage losses from irrigation canals contribute to formation of a high, non-saline aquifer that supports trees along the Colorado River's riparian corridor because subsurface seepage losses drain toward the river channel as underflow. And they estimate that about 10% of the inflows to the Mexicali Valley end up being used by "natural ecosystems" (e.g., riparian habitats on the delta). Also, the half-dozen or so riparian (fresh and brackish water) marshes of the Colorado River Delta are maintained almost entirely by agricultural return flows from Mexico and the U.S. For example, in the west, the Río Hardy marshes are sustained by brackish agricultural flows from the Mexicali Valley Irrigation District that discharge into the Río Hardy channel. In the east, Ciénega de Santa Clara, the largest brackish marsh in the Sonoran Desert, is sustained primarily by brackish water pumped from the Wellton-Mohawk Irrigation and Drainage District in the U.S. and sent for disposal in Mexico via the Main Outlet Drain Extension (MODE) canal, which supplies 95% of the ciénega's water, with most of the remainder being supplied by the Riito-Santa Clara drain that transports surface irrigation runoff from the agricultural fields of the San Luis Río Colorado Valley in Sonora (Mexicano et al. 2013, García-Hernández et al. 2013a).

Orozco-Durán et al. (2015) also used Mexican National Water Commission (CONAGUA) data to assess water balance across the delta. Those data estimated that 755×10^6 m^3 of ground water (including rain infiltration) moves across the border annually from the Lower Colorado River Basin (CONAGUA 2006, 2007, 2010; Orozco-Durán et al. 2015; W. Daesslé, pers. comm. 2015). Combined with the Carrillo-Guerrero et al. (2013) estimates of surface water (Colorado River + rainfall, see above), this yields a total freshwater influx to the delta of about 3.74×10^9 m^3 yr^{-1}. In the Mexicali Valley Basin, wells pump groundwater to the surface for use in urban centers as far away as Tecate and Tijuana, and for agricultural and industrial use. Water used outside the delta area (e.g., Tijuana and Tecate) is lost to the regional system and removed from the delta's water budget, as is water lost by evapotranspiration and in agricultural and wetland biomass production. Water used within the basin is partly recycled as it sinks back down to the water table from unlined agricultural and industrial canals, wastewater discharge, septic systems, etc. The amount of water that is removed from the system, by being exported outside the Mexicali Valley, by agricultural biomass production, and by evapotranspiration is very high. The National Water Commission estimated that less than 35×10^6 m^3 yr^{-1} (4.6%) finds its way to the Upper Gulf, through a mix of subterranean and surface flow, the latter mainly being via the Río Hardy drainage and Ciénega de Santa Clara seepage. To put this estimate in context, this is about 2%

of the 1.85×10^9 m^3 (1.5 million acre-feet) of river water annually allotted to Mexico by the water treaty. (To further put this in context, California alone uses 4.0-5.5 million acre-feet of water annually just to grow alfalfa [University of California 2016].)

The delta's aquifer is known to have high storage capacity and subterranean water moves very slowly toward the Gulf. However, the 35×10^6 m^3 yr^{-1} estimate may be too high, as some of this estimated discharge probably does not actually reach the marine environment, but is captured and impounded in freshwater artesian springs (*pozas*) along the southernmost Cerro Prieto fault, such as El Doctor wetlands near the town of El Golfo de Santa Clara, and the numerous *pozas* of coastal Bahía Adair, where it supports small refugial Colorado River Delta riparian wetland habitats.

Zamora et al. (2013) estimated that, today, less than 1% of the Colorado River's water reaches the Gulf, noting that the river's relict lowermost channel is plugged by sediment that accumulates during flood tides. Ebb tidal flows are not strong enough to keep the channel open, and weak-flowing (or no) river water cannot maintain it. During spring tide cycles, when no channel blockage was present, tidal flows could reach about 65 km upriver from Montague Island near the river's mouth due to the slight topographic gradient (about 16 cm/km) (Thompson 1968, Payne et al. 1992, Nelson et al. 2013a,b). However, without adequate river flow these penetrating tidal currents result in bedload transport from the Gulf into the lower channel which builds an obstructive, recurring tidal sand bar across the river bed about 25-30 km upstream from Montague Island (about half-way to the junction of the Río Hardy). The sand bar apparently develops when river flow is greatly reduced or absent, and is re-opened only when sporadic high-river flows occur. Anecdotal reports of a sand bar obstruction in the lower river channel appeared as early as the late 1950s (Kira 2000), but the first official report was in 1972, when Mexico's Secretaría de Agricultura y Recursos Hidráulicos (SARH) reported it 23 km above Montague Island (U.S. Army Corps of Engineers 1982). The sand bar was noted in LANDSAT satellite images by Nelson et al. (2013a,b) as early as 1972, and by Zamora et al. (2013) beginning after the year 2000, and by 2009 Zamora et al. (2013) estimated the up-channel tidal flow topped the sand bar only 12 days per year. Nelson et al. (2012a) also recorded the presence of the sand bar in 2011 using pressure-based logger data in the river channel.

Zamora et al. (2013) reasoned that the sand bar began accumulating after Glen Canyon Dam began operations in 1964, which is likely when tidal processes became dominant over fluvial processes in the lowermost river channel. During some of the unusually wet years of the 1980s and 1990s, when excess river flows were delivered to Mexico, the sand bar was apparently, at least periodically, scoured open. Payne et al. (1992) reported that the sand bar was washed away by the large 1984-1988 floodwater releases down the channel of the Colorado River. All (2006) argued that most of this discharge ended up in Laguna Salada where it was lost to evaporation, with little of it reaching the Gulf. On-site observations of the river mouth by S. M.

Nelson showed that at least some fresh water reached the sea in 1984, 1993, and 1997 (Nelson et al. 2013a,b), but the actual amount is unknown. Analysis of LANDSAT satellite images from late 1979 through 1985 indicated that the sand bar impounded flood waters during the unusually wet years of the early 1980s, resulting in flooding that connected the river channel to the Ciénega de Santa Clara at least twice (Nelson et al. 2013a). Nelson (2007) noted that the presence of the sand bar resulted in back-flooding of most of the delta during the late 1983-early 1984 El Niño (see Figure 3a), but by November 1984 the floods had finally opened a channel through the sand bar to allow the remaining (unevaporated) water to reach the sea. Connectivity between the river and Ciénega de Santa Clara ended when the river cut a new channel through the sand bar in late 1984 (Nelson et al. 2013b). Flood releases during the 1990s kept the river channel open, but a new tidal sand bar formed after 2000, when river flow again fell (Nelson et al. 2013b, Zamora et al. 2013). Nelson et al. (2013a) noted the sand bar could be seen re-forming itself in 2006 LANDSAT images, at approximately the same location as the pre-1983 bar, and by 2008 it was high enough to cross over in a two-wheel drive vehicle during neap tide periods. However, Zamora et al. (2013) felt that spring tidal bores might have been able to top the sand bar several times a year even since 2000.

The groundwater flow and surface seepage that does reach the Upper Gulf has the potential to contribute some dissolved nitrates and silicates to the sea. However, most nitrates in surface and ground waters in the Mexicali Valley are derived from agriculture drains and sewage waste, and these might enter the Gulf primarily by surface seepage via the Ciénega de Santa Clara wetland. Their potential average annual contribution (via the ciénega) has been estimated at 59,400 kg $N\text{-}NO_3$ (Orozco-Durán et al. 2015). Running southeast from Ciénega de Santa Clara is the so-called Santa Clara Slough—a roughly 26,000-ha basin subject to periodic inundation from the Northern Gulf's high-amplitude spring tides, which historically reached the margin of the ciénega several times each year (Nelson et al. 2013a). The slough receives brackish water inflow from the ciénega, especially during winter months when delivery of agricultural wastewater increases and evapotranspiration decreases (Glenn et al. 2013a,b, Greenberg and Schlatter 2012). During summer months, wastewater inflow to the ciénega is reduced and evapotranspiration rates reach their highest levels of the year, thus little or no water passes through to the slough (Greenberg and Schlatter 2012, Glenn et al. 2013a,b). And, throughout the year, water exits the slough primarily through evaporation (Glenn et al. 2013a,b, Nelson et al. 2013a).

Silicates reaching the Upper Gulf, mostly in surface flow/seepage, are probably the result of ground water associated with geothermal sources in the region, and these may be a nutrient source for the large diatom populations of the Northern Gulf (which require silica to make their shells). Silica-rich brines from the delta's Cerro Prieto geothermal power station, for example, have an average value of 69.2 mg L^{-1} $Si\text{-}SiO_2$ (Orozco-Durán et al. 2015). Phosphates, however, are mostly transformed into a particle phase and precipitated out in sediments before reaching the Gulf, a process occurring at every dam the Colorado River encounters as phosphorous becomes trapped in reservoir sediments (Stevens et al. 1995, Stromberg and Chew 2002).

Agricultural return-flows to the Colorado River channel in Mexico also carry high levels of fertilizers and insecticides. For example, during the 1990-91 crop cycle, at least 70,000 tons of fertilizers and 400,000 liters of insecticides were used in the Mexicali Valley (Daesslé et al. 2009, based on DGE 1993). This has increased the organic and inorganic compounds in the upper delta region (visible in Figure 2 as the bright green of agricultural fields), including mercury, copper, arsenic, DDT, DDE, and DDD, in both surface and ground waters (García-Hernández et al. 2013b, Lugo-Ibarra et al. 2011, Daesslé et al. 2009).

Laguna Salada Basin (also known as Laguna Macuata, in the Pattie Basin, in the early 20th century) is situated in a fault depression between the massive Sierra de Juárez (of Baja California) on the west, and the 90 km-long Sierra Cucapá-Sierra El Mayor range on the east, the latter being fault-bounded ranges reaching ~1000 m in elevation (Figure 2). Laguna Salada Basin is a tectonically active pull-apart basin (described by some geologists as a western subbasin of the Mexicali Valley), a graben (or half-graben) formed by the Laguna Salada Fault on the east (part of the Pacific-North American Plate boundary system, and a probable southern continuation of the Elsinore Fault in southern California), and the Sierra Juárez Fault on the west (Mueller and Rockwell 1995, Martín-Barajas et al. 2001, Fletcher and Spelz 2009, Alles 2011, Nelson et al. 2012). Hot artesian springs were reported from the western slopes of the Sierra Cucapá by Sykes (1937) and also appeared on his 1907 map of the region. The location of the Laguna Salada Fault itself is easily recognized by surface features, such as fault scarps, faulted alluvial fans, and freshly exposed bedrock. Visible, young alluvial deposits were probably displaced during the large regional earthquakes of 1892, 2008 and 2010, and the basin itself is filled 4-6 km deep with alluvial deposits (Martín-Barajas et al. 2001).

Dry shells of the barnacle *Amphibalanus subalbidus* in Laguna Salada (2016), an Atlantic species introduced to the Colorado River Delta brackish-water wetlands in the 1980s

Like the Salton Basin, the Laguna Salada Basin has land surface elevations that lie below sea level, and the basin is lower in elevation than the Río Hardy channel at the southern tip of the Sierra El Mayor (Sykes 1937). In April 2016, we measured a low point in the upper part of the basin (~32°32'N, 115°42'W) using a hand-held GPS altimeter (calibrated 14 hours prior at sea level) at 11 m below mean sea level. Laguna Salada is a closed freshwater sink and evaporative basin, as is the Salton Sea. The northern boundary of the laguna is today effectively set by the high berm that supports Mexico's Federal Highway No. 2, which runs east-west through a pass in the northernmost Sierra Cucapá.

Compeán-Jimenez et al. (ca. 1981) estimated that Laguna Salada had the potential to lose 13,968 m^3 of water per hectare annually through evaporation, but this is probably a significant under-estimation given that they calculated the surface area at only 400 km^2 (less than half the potential areal coverage when the laguna is filled) and with a volume of just 730,106 m^3 (also probably a significant under-estimate).

The great depth of alluvial deposits in Laguna Salada clearly indicates that it has served as a flood-drainage basin for the Colorado River for millennia, and historically, during flood years, water also drained from the mainstem of the Colorado River (below the confluence with the Río Hardy) into the laguna, by way of the topographic low between the southern tip of the Sierra Cucapá-Sierra El Mayor range, and the northern tip (*El Promontorio*) of the Sierra de las Pintas (Sykes 1937, Mueller and Rockwell 1995, Cohen and Henges-Jeck 2001). Sykes (1937) described flood flows filling Laguna Salada numerous times during his field studies, between 1910 and 1932. In the late 19th century it supported a valuable subsistence fishery for the indigenous Cucapá People (when it was called Laguna Maquata). However, construction of

Hoover and Glen Canyon Dams cut off the lake's freshwater inflow (the Colorado River) and that fishery was destroyed as the lake dried. Laguna Salada had a resurgence in the late 1970s and early 1980s, during flood years, but those surface waters quickly evaporated (Álvarez de Williams 2007, Brusca 2007). Nelson et al. (2013a) suggested that flow into Laguna Salada may have largely ceased in 1986. However, large precipitation events in the Southwest could lead to it refilling in the future.

The size of the laguna is highly variable, ranging from completely dry to nearly 1000 km^2 in area of surface water. The Laguna Salada Basin itself exceeds 90 km in length, paralleling the western flanks of the Sierra Cucapá-Sierra El Mayor range (Figures 2 and 3; also see Figure 1.1 in Cohen and Henges-Jeck 2001 and the 1937 Sykes' map). Compeán-Jiménez et al. (ca. 1981) cited the laguna as approximately 400 km^2. However, All (2006) reported it at ~1000 km^2, various Arizona Geological Society maps show it at just over 1000 km^2, Mueller and Rockwell's (1995) map shows it at ~800 km^2, Mexico's official INEGI map (Instituto Nacional de Estadística, Geografía e Informática, 1993) shows it at over 800 km^2, Sykes (1937) measured the basin at 1,280 km^2, and the cartography of the American Automobile Association map depicts it at around 950 km^2. GIS maps of the delta show the "bathtub ring" area of Laguna Salada to be 990 km^2 in size, which is the same as the LANDSAT image of the filled laguna in 1984 (Figure 3a), although the <u>total</u> amount of flood water trapped on the delta in June 1984 was approximately 2500 km^2. The high-water line of Laguna Salada is also easily recognized in Google Earth satellite images, and the calculated size of this area (using a polygon algorithm provided in Google Earth) is just under 1000 km^2. The entryway to the basin, which can be breached by heavy river flows (especially when combined with high spring tidal flows up the river channel), is south of the Sierra Cucapá-Sierra El Mayor range, as shown in Cohen and Henges-Jeck (2001, p. 3), Sykes (1937), Mexico's INEGI maps, and satellite imagery (Figure 3). The prominent "thumb" at the southern end of the Laguna Salada Basin, demarcated by the northern point, or *Promontorio*, of the Sierra de las Pintas, is evident in Sykes's 1937 map and in satellite images (Figure 3).

Using NASA images over a span of nearly two decades, All (2007) showed the extreme ebbs and flows of water into Laguna Salada and that during the 1980s flood years (at least the first half of the decade) about 1000 km^2 were inundated. In fact, what matters is not the amount of water in the basin at any given time (such as the Compeán-Jiménez et al. "snapshot in time"), but the <u>capacity</u> of the basin itself, which is approximately 1000 km^2.

Laguna Salada can also form as a small lake during summer monsoon rains, but it is often completely dry. However, even when Laguna Salada appears "dry" it commonly is not, because of its high capacity to store interstitial water in the deep, silty, alluvial sediments extending beneath its surface, and this water bank can be covered by a 2.5 to 7.5-cm-thick cap of crystalized salt. As with All (2007) and Álvarez de Williams (2007), we have had our 4-wheel-drive vehicles stuck more than once attempting to drive across what appeared to be a dry lake bed that actually had a thick layer of water-saturated mud just below the crystallized salt surface.

Evidence of Laguna Salada flooding also comes from records of the brackish-water barnacle *Amphibalanus subalbidus* (formerly *Balanus subalbidus*). This West Atlantic-native barnacle can live in nearly freshwater salinities (Poirrier and Patridge 1979) and seems to have found its way into the Colorado River Delta in the wet years of the 1980s. In 1989, A. Boetzius found specimens of *A. subalbidus* in a dry portion of Laguna Salada Basin, and, in the same year, barnacle specialist R. Van Syoc found living specimens in a flooded part of the laguna (Van Syoc 1992). In 1989 Álvarez de Williams (2007) found dead shells in Laguna Salada, in 1990 Van Syoc found dead shells in the Río Hardy, and in 1991 R. Brusca found dead shells in a dry peripheral area of Laguna Salada; the latter specimens had been growing in profusion at a height of 1.5 m on dead shrubs in the westernmost part of the basin (Brusca 2007). In 2002, barnacle specialist W. Newman found living *A. subalbidus* on the delta again, but this time in agriculture canals at New River and Colonia Zacatecas, suggesting that there had been an exchange of water between there and Laguna Salada, possibly during the huge 1983-1984 flood that inundated the delta (Newman, pers. comm.). *Amphibalanus subalbidus* is native to the Gulf of Mexico and has never been reported from the Gulf of California (or anywhere else in the East Pacific) in modern times. This barnacle is well known from estuarine habitats in the Gulf of Mexico (Poirrier and Partridge 1979). Van Syoc (1992) concluded that the modern-day *A. subalbidus* is the same species as the fossil barnacle, *Balanus canabus* Zullo and Buising, 1989, described from the Bouse Formation of the lower Colorado River area of Arizona and California, and Van Syoc (1992) relegated the latter species to a junior synonym of *A. subalbidus*. This last discovery suggests that this now-West Atlantic species once lived in the Colorado River Delta, but then went locally extinct, only to be reintroduced in recent times. Dead specimens of *A. subalbidus* can be found embedded in the sediments throughout the laguna today (Figure 5).

The topographical gradient of the Colorado River in the lower delta region is so slight (about 16 cm/km; Thompson 1968) that the river loses its firm channel and becomes a meandering network of small streams, oxbows, sloughs, and backwaters. The expanse of the delta between the southern end of the Laguna Salada Basin (on the west) and the Ciénega de Santa Clara wetland (on the east) is low-lying mudflat that can become inundated by brackish water during now-rare flood events of the Colorado River, and much of it can also become saturated with seawater during the highest spring tides in the Upper Gulf. Today, this lower-most delta region is fundamentally marine in nature, not riparian. Much of it is vegetatively dominated by the endemic marine grass *Distichlis palmeri* (Felger 2000). In fact, the final 19 km of the Colorado River has been viewed as part of the Upper Gulf's intertidal zone (Cohen et al. 2001). Because flood flows down the Colorado River channel in this lowermost delta region are not naturally well channelized, water thinly spreads out over the entire area.

Responding to a long history of flooding on the delta (and loss of homes and agricultural land), the Mexican government channelized much of the region, diverting most of the lowermost delta water flow directly into the Laguna Salada Basin. In 1974, a 3 m-deep canal was constructed to move floodwaters from the Colorado River and lowermost delta (Irrigation District No. 14) into the basin. The government also excavated the Canal Alimentador (Feeder Canal), near the Cerro Prieto geothermal power generating plant just east of the Sierra Cucapá, that moved floodwaters from the west-central Mexicali Valley to Laguna Salada. The 1983-84 floods washed out a large, natural earthen berm along the Río Hardy channel, which had acted to keep water in the channel, and thus flowing to the delta wetlands. After this event, however, overflows were diverted into the Laguna Salada Basin via the Laguna Salada Canal.

The 24 km-long Río Hardy (a former channel and now tributary of the Colorado River) collects water from the eastern watershed of the Sierra Cucapá-Sierra El Mayor range, as well as flood, agricultural, and various waste waters from the western Mexicali Valley. With declines in precipitation over the past 25 years, most of the Río Hardy flow is now from agricultural drainage, wastewater of the Cerro Prieto geothermal wells (which began operating in 1973), and wastewater from the Arenitas secondary sewage treatment plant (that flows through the small Las Arenitas wetland, recently created by local conservation groups in collaboration with the state government to help biologically treat the outflow from the plant). The Río Hardy water is thus of poor quality; it is high in total salts and may contain pesticide residues, heavy metals, selenium, and nitrates from fertilizers. During most high-flow events from 1983 to 1985, water apparently flowed from the Río Hardy more or less directly into Laguna Salada. However, Nelson et al. (2013a,b) also documented at least some of the flood flow in the river channel all the way to the Gulf in 1984, 1993 and 1997, so not all of the delta's water was impounded in the laguna.

The government report by Compeán-Jimenez et al. (ca. 1981) found *Tamarix ramosissima* (tamarisk, salt cedar) and *Typha latifolia* (cattail) to be the dominant macrophyte vegetation at Laguna Salada. The study also found 11 species of freshwater fishes and 2 species of crustaceans—none indigenous to the Colorado River south of the U.S.-Mexico border, and all introduced from California and Arizona, probably via the flood flows that crossed the international border. In addition, some marine euryhaline species immigrated into the laguna from the Sea of Cortez—striped mullet (*Mugil cephalus*), machete (*Elops affinis*), small squids, etc. In the past, high spring tides in the Upper Gulf occasionally reached the laguna, periodically introducing marine species of fishes and invertebrates. This largely ended with construction of Mexico's Federal Highway No. 5, running south to San Felipe. Although the floodwater connection of Laguna Salada to the Sea of Cortez may have largely been closed in the early 1980s, the euryhaline striped mullet was apparently able to spawn and recruit in brackish water and individuals have been sporadically reported from irrigation waters of the Mexicali Valley ever since at least 1967. It has been suggested that the floods of the 1983-84 El Niño might have destroyed most of the diversion canals leading to Laguna Salada, but the extent and impact of this is unclear, as is any channeling that might have been repaired or rebuilt since that event.

The major impact of all these sinks and natural and man-made diversions in the delta, that redirect surface-water flood flows in the Colorado River channel, has been to prevent river water from directly reaching the Gulf of California. As a result, since the mid-1970s only during the flood years of 1978, 1982-1988, 1993, and 1997-1999 is it likely that any significant Colorado River surface water could have reached the Upper Gulf (seepage out of Ciénega de Santa Clara aside). The amount that actually reached the Gulf during those flood years remains a hotly debated topic.

ENDNOTE 6. Bahía Concepción is one of the best examples of a mini-extensional basin in the Gulf. This huge and stunningly beautiful bay, 25 mi (40 km) in length and 105 mi^2 (270 km^2) in area, formed along the eastern edge of the Baja California Peninsula during the opening of the Gulf, and its long and narrow shape results from a half-graben created by northwest-southeast trending faults, the eastern one (Bahía Concepción Fault) lying on the Peninsula Concepción. With a length of 25 mi (40 km) and an area of 100 mi^2 (270 km^2), 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 Ma) granodiorite outcrops. The shallow bay, mostly 25–30 m (80–100 ft) depth, was probably a non-marine basin during most of the Pleistocene, when sea levels were much lower (during glacial cycles).

Bahía Concepción, Baja California Sur

ENDNOTE 7. A number of phylogeographic studies of terrestrial animals on the Baja California Peninsula have been published over the past 40 years. Phylogeography is the study of geographical distributions of genealogical lineages (today, primarily based on analyses of DNA sequence data). Analyses of these types can provide clues to past events that have affected animal/plant distributions, such as the location of possible vicariant events, biological refugia, the establishment of strong ecotones, major climatic oscillations during the Pliocene-Pleistocene-Holocene, marine transgressions, etc.

Baja California, the second longest peninsula in the world (~800 mi/1300 km in length), seems an ideal place to study terrestrial phylogeography. Indeed, significant phylogenomic breaks within a variety of species (and species groups) have been suggested to occur at various locations throughout the peninsula. In searching for possible causes of these genetic breaks, some biologists have hypothesized transient, “trans-peninsular seaways” that might have existed in the past; temporary barriers to dispersal that resulted in genetic breaks between isolated populations or species. Most of these phylogenetic breaks have been recorded from three general areas, leading to the proposal of three possible trans-peninsular seaways: (1) a “mid-peninsular seaway” (somewhere between 26° and 29° N), sometimes called the “Vizcaíno seaway” and sometimes suggested to be an ancient extension of Laguna San Ignacio; (2) a “Loreto seaway” (which has minimal phylogenomic support); and (3) an “Isthmus of La Paz seaway," near the tip of the peninsula (between 30° and 32° N). However, it is important to note that there exists no solid geological or paleontological evidence supporting the idea that any of these would have actually connected the Pacific Ocean to the Sea of Cortez. There are no marine sediments that completely cross the Baja California Peninsula at or near the locations of any of these hypothetical "seaways" (Darton 1921, Oskin and Stock 2003, Bennett et al. 2015). And, the peninsula is actually one massive, solid, and buoyant continental block, or terrane, that is likely to be preserved n any future accretion to the North American continent (Umhoefer and Dorsey 2011). Instead, the geologic evidence suggests the possible presence of Miocene embayments on the continental margin of Mexico prior to the Gulf's opening. There is a broad mix of suggestions for the ages of these putative seaways, and almost no suggestions for what their durations might have been.

A close examination of the data upon which these phylogenetic breaks are based, and the data that might support past trans-peninsular seaways in general, finds only mixed support. Some of the arguments against the seaway hypotheses are as follows.

(1) Until recently, almost of the species' deep phylogenomic breaks on the peninsula were based solely on mitochondrial DNA (mtDNA) data. Mitochondrial trees depict only maternal lineages, because DNA is maternally inherited (and usually as a single copy). In fact, as of 2014 only 3 species from analyses of nuclear genes had shown significant phylogenomic breaks. And, importantly, none of these species showed congruent phylogenomic breaks using both mtDNA and nuclear DNA. Furthermore, many of the mtDNA analyses have since been shown to be in error or lacking significant results. Furthermore, many researchers (e.g., Niegel & Avise 1993, Heeler 2001, Irwin 2002, Kuo & Avise 2005) have demonstrated that genealogical splits may form within a continuously distributed species simply due to the hierarchical, female-restricted, and non-recombining inheritance of mitochondrial DNA, given sufficient time. Even in the absence of barriers to dispersal, deep breaks in a mtDNA gene tree can arise haphazardly at essentially any location along a species' linear distribution, especially in species with low dispersal capacities that are spread over a long linear range such as a peninsula. Coalescence simulations have confirmed that deep phylogenomic breaks can arise relatively quickly in the mitochondria whenever the effective size and the time (in generations) are on the same order of magnitude, in regions where migration has never been completely hampered in the past. Vicariance, therefore, is not required to produce deep divergences in mtDNA along a narrow peninsula such as Baja California. Additionally, it is well known that mitochondrial genes alone can produce misleading phylogenetic trees, due to factors such as historical hybridization and introgression. In today's world no one would seriously rely on mtDNA trees to produce phylogenies among species. In fact, multiple nuclear genes, or even genomic approaches, are now viewed as the most reliable way to recover phylogenies. Most recently, researchers have developed multigene methods that

do not require strict gene tree monophyly, but rather, allow for some gene tree heterogeneity while delimiting species using multispecies coalescent models (Leache & Fujita 2012; Fujita et al 2012; McKay et al 2013; Rannala & Yang 2013).

(2) A conspicuous characteristic of the peninsular "deep phylogenomic breaks" is their cryptic nature. That is, the morphological, behavioral, and ecological traits of the species populations show no, or few, correlations to the mtDNA-based phylogeographic breaks—a telling clue that the mtDNA data might not be accurately revealing past species evolution.

(3) Phylogenomic breaks can be explained by ecological gradients caused by abrupt changes in phytogeography and weather patterns, followed by adaptation to local selection regimes. In fact, current-day phytogeographic regions correspond well to all of the proposed ancient seaway locations. The most frequently cited deep phylogenomic break, the mid-peninsular seaway, coincides with the southernmost record of early Holocene Baja California woodland and chaparral vegetation, according to packrat midden data. This suggests that the central Baja Peninsula experienced a mild Mediterranean-type climate of 5°-6° C cooler than the climate of today, with perhaps twice the winter precipitation that the region now receives. For example, a packrat midden at 2560 ft, from the western slopes of the Sierra San Francisco (BCS) dating to ~10,200 ^{14}C yr BP (Younger Dryas cool interval) contained remains of California juniper (*Juniperus californica*) and other taxa now associated with Southern California chaparral (California juniper does not occur in the Sierra San Francisco today) (Rhode 2002). The hypothesized mid-peninsular seaway region also coincides with a strong transition zone between two major botanical provinces—the Vizcaíno Desert in the north, and the Magdalena Desert to the south. These subregions are separated by volcanic mountain ranges (Sierra San Francisco and Volcán Las Tres Virgenes) where extensive lava flows over the past 1.2 Ma, perhaps as recently as the Late Holocene, effectively wiped out existing vegetation. This ecological history alone is likely sufficient to account for the spatial-genetic patterns seen in plants and animals of the region (see below).

(4) The timing and duration of the three proposed trans-peninsular seaways are ambivalent. The age of the most frequently-cited location, the mid-peninsular seaway, has been suggested to be as young as 1-1.5 Ma to as old as 13-15 Ma. The older date, of course, is before the peninsula even existed, and any coastal embayments would have been much further south in latitude (in the tropics). The youngest date appears to be geophysically impossible, because at 1 Ma the geomorphology of the peninsula was essentially the same as it is today. All mountain ranges had reached their current elevations, the Gulf had achieved its current position, and there was a land connection between the Sierra de la Giganta and the Cape Region. Thus, there would have had

to be a 300 m sea level rise to create a mid-peninsular seaway, which would have re-inundated most of southeastern California and the Isthmus of La Paz, leaving behind ample traces in the geological record (but, no such evidence has been found). Helenes and Carreño (1999) attempted to offer some paleontological support for a Miocene mid-peninsular seaway, based on fossils occurring on either side of the peninsular in the Bahía San Ignacio area, but they did not document a continuous series across the peninsula nor did they convincingly demonstrate that their “trans-peninsular seaway” could have been anything more than an ancient embayment on the mainland coast of south-central Mexico prior to opening of the Sea of Cortez.

(5) Molecular clock data that have been used in support of the timing of phylogenomic breaks on the peninsula are largely inadequate (often based on a single fossil for timing) and of questionable value.

(6) A recent analysis (Graham et al. 2014) of scorpion species on the Baja California Peninsula, using species distribution models (aka, ecological niche models) compared current suitable habitat with that of the last glacial maximum (~21,000 ybp). Their results suggest that most peninsular scorpion distributions remained remarkably conserved across the last glacial to interglacial climatic transformation. The predicted habitat for all but one of the 13 species studied was stable across the peninsula since the Last Glacial Maximum (LGM), suggesting that suitable habitat for scorpions of Baja has remained remarkably stable since the LGM. This provides evidence that long-term climatic stability, not vicariance/seaways, may have produced patterns of divergence seen today between species. Current-day scorpion niche models show four regional distribution patterns along the peninsula: northern peninsular, mid-peninsular, southern peninsular, and the Cape Region. The niche models of several potential sister-species pairs display a sharp decrease in climatic suitability in the same three regions that have been hypothesized to sites of trans-peninsular seaway breaks. Thus, Graham et al. “find it conceivable that genetic discontinuities could have arisen in association with localized adaptation to differential climate regimes.” Similarly, González-Trujillo et al. (2016) found no genetic breaks in the wolf spider *Pardosa sierra* in regions where the mid-peninsular and Isthmus of La Paz channels presumably existed. Additionally, Gutiérrez-Flores et al. (2016), using microsatellite markers and ecological niche modeling, concluded that the distribution of cardón cactus (*Pachycereus pringlei*) on the peninsula is the product of Pleistocene/Holocene climatic fluctuations, not vicariance events. They interpreted their data as evidence of repeated environmental oscillations that caused cyclical changes in the distribution of plant communities. They hypothesize that the genetically-distinct northern and southern cardón populations on the peninsula arose through a series of range expansions and founder events that reduced gene flow, combined with genetic drift. Cardón has a distributional pattern similar to that of pitaya agria

(*Stenocereus gummosus*) and senita (*Lophocereus schottii*), and all three species of columnar cacti probably achieved their current distributional range via range expansion from a glacial refuge in the southernmost Peninsula after the end of the Last Glacial Maximum—with no need to evoke "transpeninsular seaways." This scenario also fits the overall plant community patterns revealed by fossil packrat middens in Baja California and Sonora.

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). Smith's study was a summary of fossil marine molluscs from northwestern Mexico, from which she drew inferences of hypothetical 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 proposed by 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 Ma) seaway as far north as the Salton Trough (e.g., the Imperial Formation of San Gorgonio Pass, California). All of these would have 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 Ma, 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 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.

However, and importantly, Smith (1991) used early-published dates for the important Isla Tiburón marine rocks (~12.9 Ma) as a guide for dating several other megafossil locations throughout the Gulf. These dates have shown to be incorrect, and later work confirmed these rocks to be 6.2 – 4.3 Ma (Oskin and Stock 2003, Bennett et al. 2015), rendering much of Smith's hypothesis construction erroneous.

It is also worth bearing in mind the numerous glacial episodes during the Pleistocene, punctuated by brief interglacials, which drove animals and plants north and south in latitude (as well as up and down mountain slopes) as they responded to climate change. During the glacials, the desert biota of the Southwest was pushed south to warm refuges in low-lying regions of Sonora and the central/southern Baja California Peninsula. During the interglacials, desert communities likely re-assembled in ways that were unique to each event. Antinao et al (2016) documented periods during the late Pleistocene/early Holocene when tropical storm intensity was much greater than today, and these wet periods no doubt affected animal and plant distributions on the peninsula. Even today, with rapid climate change in the Southwest, communities are re-assembling, changing as species respond individualistically to warming. And even in the Holocene, there have been periods of rapid cooling (e.g., the Older Dryas, Younger Dryas, etc.) and rapid warming (e.g., Mid-Holocene Thermal Maximum, Medieval Climate Anomaly, etc.) that would also have created new climate-based boundaries for animal and plant populations. All of these events likely played roles in creating the genetic patterns seen today in the biota of the Baja California Peninsula.

Zoologists working on the peninsula have been surprisingly naïve about the large body of phytogeographic research in the region. The complex topographically- and climatologically-driven biogeography of the Baja Peninsula is well known (it has been described in detail by the botanical research community), and it supports a flora of over 4000 plant taxa, fully 850 of which are endemics. The 1300 km (800 mi) long latitudinal span of the peninsula extends across the seasonal, warm-temperate California Floristic Region to the hot, tropical Cape Region. As a result, Baja California is a long biological transition area, from a northern winter-rain dominated warm-temperate region to a southern tropical dry forest soaked by late-summer storms, with an extensive desert in between. The narrow peninsula also exhibits a strong east-west transition. The Pacific coast is strongly influenced by the cool California Current and has a foggy oceanic climate, whereas the eastern coast is exposed to the warm waters of the Sea of Cortez and is more continental in nature. In addition, the peninsula has a mountain backbone that runs its length, creating strong elevational gradients and a rain shadow effect, the latter giving the Gulf slopes a much drier climate than the Pacific slopes. The western slopes intercept Pacific moisture from ascending air masses and are much cooler and wetter than the lowlands or the eastern slopes.

Overall, botanists and ecologists recognize three large floristic provinces in the peninsula—the California Floristic Province, the Sonoran Desert, and the Tropical Cape Region. Within each are numerous subdivisions. For example, the California Floristic Province (a Mediterranean biome), is represented by the California Mountains Subprovince (a continuation of the Transverse and Peninsular Ranges of California)—the Sierra de Juárez and Sierra de San Pedro Mártir. Together with the Sierra de La Laguna (the Cape Mountains) in the south, these ranges extend coniferous forests all the way to tip of the peninsula. The California Floristic Province is also represented by Chaparral, Coastal Sage Scrub, and Coastal Succulent Scrub communities. Within the long Sonoran Desert Region are subprovinces recognized as Lower Colorado Desert, Central Desert, Central Gulf Coast, La Giganta Ranges, Vizcaíno Desert, and Magdalena

Plains—each a distinct ecoregion with their own floras. The Cape Region has Cape Lowlands and Cape Mountains (Sierra de La Laguna) subdivisions.

Gottscho (2014) proposed the thought-provoking hypothesis that four major biogeographic breaks on the northwestern coast of North America, for both littoral and terrestrial biota, correspond with the four Great Pacific Fracture Zones on the Pacific Plate. The four biogeographic breaks he identifies are (1) Cape Mendocino and the North Coast Divide, (2) Point Conception and the Transverse Ranges, (3) Punta Eugenia and the Vizcaíno Desert (Baja California Peninsula), and (4) Cabo Corrientes and the Sierra Transvolcanica. These are said to correspond to the following fracture zones, respectively: Mendocino Fracture Zone, Murray Fracture Zone, Molokai-Shirley Fracture Zone, and Clarion Fracture Zone. These great fracture zones are, in turn, the product of transform faulting along spreading centers associated with the evolution/migration of the Mendocino and Riviera Triple Junctions and San Andreas Fault System. Gottscho further hypothesizes that the enigmatic Transverse Ranges of southern California are actually a rotated fragment of the ancient Farallon Plate, whereas the Sierra Transvolcanica of Mexico (which are aligned with the Clarion Fracture Zone, east of Cabo Corrientes) is continental deformation related somehow to the Rivera Triple junction.

ENDNOTE 8. The Colorado Plateau encompasses 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 Ma. The uplift of the plateau may have begun ~25 Ma and continues today. The amount of uplift has been estimated at 350–2200 m (1150–7220 ft), 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 shallow-angle subduction of the Farallon Plate beneath North America.

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 actually a succession of at least four lakes that filled the valley long before the man-made creation of the Salton Sea in 1905. These lakes were 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 “bathtub rings” of distinctly-colored sands, and also as a band of travertine deposits ~12 m (42 ft) above mean sea level throughout the region (Blake 1854, Hubbs et al. 1963, Thompson 1968). Travertine (or “tufa”) is a freshwater calcium carbonate deposit created by algae living along shallow lakeshores or, occasionally, at geothermal springs. The times of Lake Cahuilla’s lacustrine environments are still debated but might have been around 40,000 years ago (see Waters 1983). However, we do know that the river filled the Salton Basin on at least several occasions during the last 1500 years (Thompson 1968); the most recent one was present before the year 1200 A.D. and was gone by the time Spanish explorers entered the region in the late 16th century. Thompson (1968) estimated it would take about 19 years for the Colorado River to fill the Salton Basin to capacity, and Wilke (1978) estimated that it would take 12 to 20 years to fill Lake Cahuilla to an altitude of 12 m. A diversion of about 50 percent of the outflow of the river would have maintained the lake level at basin capacity (Thompson 1968). Evidence clearly indicates that the Lowland Patayan and early Cahuilla cultures used the resources of the lake. Evidence suggests that freshwater lakes probably existed intermittently in the Salton Trough throughout 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 (40 ft) above sea level. In addition, the river flowed to the Salton Basin (instead of the Sea of Cortez) at least a half-dozen times during the 19th century, creating temporary lakes.

Lake Cahuilla has been known in the scientific literature at least since 1854 (Blake 1854). Waters (1983) described the late Holocene chronology of the lake, linking it to regional archeology. The lake formed at least 3 (Wilke 1978) or 4 (Waters 1983) times in response to the western diversion of the Colorado River into the Salton Trough. On each occasion, the lake refilled until the water level reached an elevation of ~12 m, the minimum crest elevation of the Colorado River Delta at Cerro Prieto. Lake Cahuilla at this elevation had a surface area of over 5700 km^2, and a maximum depth of ~95 m. Eventually the river would redivert its flow back to the Gulf of California, causing Lake Cahuilla to evaporate slowly. Wilke (1978) estimated it would take about 60 years to desiccate Lake Cahuilla (at a rate of 1.8 m/yr); Waters (1983) estimated 110 years. Wilke (1978) estimated the last three lake intervals to have been: 100 B.C. to 600 A.D., 1250 to 900 A.D., and 1500 to 1300 A.D., although Waters (1983) questioned the accuracy of these dates. Waters proposed 4 recent lake periods, all within the last 2000 years, between 700 and 1580 A.D. (±100 years), plus an unknown number of lakes that might have occurred prior to A.D. 1. Sykes (1914) estimated that the river created freshwater lakes in the Salton Trough in 1840, 1842, 1852, 1859, 1862, and 1867.

ENDNOTE 10. Prior to construction of Hoover Dam, larger amounts of fresh water frequently discharged into the Upper Gulf of California. The largest river flows have always been associated with snowmelts and rains in the upper Colorado River Basin, and occurred May to August (peaking in June). Today, however, due to excessive damming of the Colorado River, beginning with Hoover Dam in 1935, and multiple water diversions on both sides of the U.S.-Mexico border, almost none of the Colorado River flow reaches the Gulf of California except in extremely wet years. The filling of Lake Mead (which Hoover Dam impounds) continued into the 1940s. Reduced water flows across the border occurred sporadically after Lake Mead filled, until construction of Glen Canyon Dam and the filling of Lake Powell, which took from 1963 to 1980, during which time practically no water flowed across the border into Mexico. After that, from 1980 to 1988, and in 1993 and 1997-2000, water releases into Mexico, through Morelos Dam, periodically occurred due to flood conditions and release protocols. The 1980s and 1990s were two of the wettest decades in history in the U.S. Southwest. However, even in those wet years with increased border releases, most of the water rarely reached the Gulf of California, being diverted by a broad variety of canals, drainages, and sinks in the Mexicali-San Luis Río Colorado region, east of the Sierra de Juarez of Baja California, where much of it was lost to evaporation. Overall, since at least 1960, the most consistent source of water to the lower Colorado River Delta has been agricultural and waste water drainage, which has provided ~40% of the total inflows to the Colorado River-Río Hardy mainstem complex in non-flood years (Cohen et al. 2001, Orozco-Durán et al 2015). During non-flood years, most of the Colorado River beyond Morelos Dam is dry all the way to its junction with the Río Hardy, at which point it usually regains surface water due to a combination of agricultural and wastewater drainage from the Río Hardy and inflow of seawater during high spring tides.

Today, Colorado River surface water enters Mexico via the Morelos Dam, which is not a storage facility but a diversion and switching station. Here, the entire flow from the Colorado River is normally diverted into irrigation channels. The quality of water coming to Mexico from the U.S. was not a serious issue until 1961. Through the 1950s, rapid population and agricultural growth in the Southwest began to create large demands for Colorado River water. Excess water became scarce and Arizona began pumping highly saline agricultural drainage water (from the Wellton-Mohawk Irrigation District) back into the Colorado River, increasing salinity and adding agricultural byproducts. In November 1961, Mexico formally protested that the salty water it was receiving was not suitable for agricultural use, and thus the U.S. was in violation of the 1944 U.S.-Mexico Treaty on the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande (the “water treaty”), which committed 1.5 million acre-feet (1.85 X 10^9 m^3) of the Colorado River’s annual flow to Mexico. In fact, the salinity had climbed from 800 ppm to nearly 1500 ppm. It took over 10 years for a proposed solution to this problem to be formally accepted. In 1973, an agreement was signed (Minute 242 of the water treaty) that the U.S. would meet standards of average water quality by building a desalination plant near Yuma, Arizona, to process the water from the Wellton-Mohawk diversion. In the meantime, while the plant was being constructed, the U.S. built a bypass channel to carry the Wellton-Mohawk agricultural drainage to the Ciénega de Santa Clara. As a result, the Ciénega grew from ~200 ha (2 km^2) to ~20,000 ha (200 km^2), and it is now the largest wetland on the Delta. This bypass, and selective pumping of the Wellton-Mohawk drainage wells, led to a slight reduction in salinity of Mexico’s water allotment to 1245 ppm (0.1245 percent). The desalination plant was built and has had three brief test runs, but operation costs and brine disposal issues have so far kept it from going into full operation. In 2007 Nagler et al. reported the salinity of the Colorado River at the international border to be nearly 1000 ppm (inadvertently reported as 1000 ppt in Nagler et al. 2007).

Before the damming began, the Colorado River is estimated to have delivered an annual average of somewhat less than 15×10^9 m^3 of fresh water and 160×10^6 million metric tons of sediment to the Delta (Carriquiry and Sánchez 1999). Harding et al. (1995) estimated pre-dam annual river discharge ranged between 8×10^9 and 30.8×10^9 m^3 yr^1. Today, the Delta is no longer receiving sediment and instead is being slowly washed away by tides and currents. The main source of suspended sediments to the Northern Gulf today is from erosion of ancient Colorado River Delta deposits (Carriquiry et al. 2011).

Beginning with the Colorado River Compact of 1922, and followed by several pursuant acts, amendments, and agreements, seven western U.S. states and Mexico have been allocated a total annual water volume that exceeds typical flows in the Colorado River. A total of 9.3×10^9 m^3 (7.5×10^6 acre-feet, 3.2×10^{11} ft^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). The 1944 water treaty guarantees Mexico 1.85×10^9 m^3 (6.53×10^{10} ft^3) of water per year. In Arizona and California, about 70 percent of the River's 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 borderland today.

ENDNOTE 11. The freshwater fauna from the El Golfo Badlands includes pond slider turtles (*Chrysemys scripta*), beaver (*Castor* sp.), Colorado River toad (*Bufo alvarius*), mud turtle (*Kinosteron* sp.), and Curtis' cotton rat (*Sigmodon curtisi*). Woodland species include deer (*Odocoileus* sp.) tapir (*Tapirus* sp.), two ground sloths (*Megalonys wheatleyi* and *Nothrotheriops* sp.) and the boa constrictor (*Constrictor constrictor*). Grassland species include two horses (*Equus complicatus* and *Equus* sp.), and the camelids *Titanotylopus* sp., *Camelops* sp., and *Hemiauchenia* sp.). Johnston's hyena (*Chasmaporthetes johnstoni*) and red wolf (*Canis* cf. *C. rufus*) are also found in the Badlands fauna. 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. The El Golfo Badlands fauna also correlates well with the Irvingtonian faunas from Vallecito-Fish Creek of the Anza-Borrego Desert in southern California (Downs and White 1968).

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 unconsolidated 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. The highest sand dunes (west of Sierra del Rosario) have a relief, from trough to crest, of 80 to 150 m.

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 100 m (330 ft) 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 Gulf of California is the only semi-enclosed sea in the Eastern Pacific, and it maintains a high net evaporation rate. Bray (1988) estimated the total annual evaporation for the entire Gulf to be 0.95 m yr^{-1}, Lavín and Organista (1988) estimated the evaporation rate for the Northern Gulf at 0.9 m yr^{-1}, and Lavín et al. (1998) estimated an evaporation rate in the Upper Gulf of 1.1 m yr^{-1}. Annual net evaporation - precipitation - runoff has been estimated at 0.61 m yr^{-1} over the entire Gulf (Beron-Vera and Ripa 2002). Average annual rainfall in the Northern Gulf is only ~68 mm yr^{-1} and is highly variable (Miranda-Reyes et al. 1990). Unlike some other semi-enclosed seas (e.g., Mediterranean Sea, Red Sea) where tidal mixing is not significant, the Gulf gains heat on an annual average, and it has long been recognized as the only evaporative basin in the Pacific Ocean (Roden 1958, 1964, Bray 1988, Lluch et al. 2007, Paden et al. 1991). Because of heat gain and evaporation, salinities in the Gulf have always been higher than in the adjacent Pacific at the same latitude. In coastal wetlands (*esteros*, or negative estuaries) of the shallow Northern Gulf salinities are even higher. Thus the flora and fauna of the Gulf, particularly the Northern Gulf, have long been adapted to life at high salinities.

Surface salinity at the mouth of the Colorado River (around the large tidal mud/sand islands of Montague and Pelícano) averages around 37 to 38‰, and increases to the northwest (within the delta itself), with a seasonal maximum of ~39‰ in August, and a minimum of ~37‰ in December-March (Álvarez-Borrego and Galindo-Bect 1974, Álvarez-Borrego et al. 1975, Bray and Robles 1991, Lavín et al. 1995, 1998, Lavín and Sánchez 1999, Álvarez-Borrego 2001, Lavín and Marinone 2003). Álvarez-Borrego and Schwartzlose (1979) used March 1973 data to describe a winter convection with high salinity and low temperature water moving close to the bottom from the Upper Gulf southward to near Ángel de la Guarda Island, reaching depths of >200 m and characterized by high dissolved oxygen. Cintra-Buenrostro et al. (2012) used oxygen isotopes in the shells of the clam *Mulinia modesta* (cited as *Mulinia coloradoensis*, a junior synonym) to estimate salinities prior to the construction of dams on the Colorado River and found that it might have ranged from as low as 22-33‰ at the river's mouth (Montague Island) to 30-38‰ 40 km southward down the Baja California coast, suggesting at least a periodic, localized river dilution effect.

A direct measurement of salinity changes in the Upper Gulf, under high river flow conditions, was made by Lavín and Sánchez (1999) recording oceanographic conditions in the Upper Gulf during a large El Niño-driven water release in 1993. That year, nearly 19 X 10^9 m^3 of river water crossed the border into Mexico. This was at a time when the delta had become highly channelized, so virtually all the water went staight to the Gulf. Even in this high-flow situation, the dilution effect on the Upper Gulf's waters was minimal. Salinity decreased from 35.4 to 32.0 parts per thousand for a few weeks, and the effect extended only along the uppermost western shore of the Gulf from Montague Island (the beginning of the delta) to San Felipe. Thus, the idea of the entire Upper Gulf having continuous freshwater flow and being low salinty year-round in pre-dam years is not supported by the data.

Surface waters in the Gulf change in response to seasonal (i.e., monsoonal) and long-term (i.e., El Niño-Southern Oscillation, ENSO) climatic events (Kahru et al. 2004, Lluch-Cota et al. 2007). Predominately northerly winter winds are replaced at the onset of the summer monsoon season (variously called the "Mexican monsoon," "North American monsoon," and "Southwest monsoon") with southerly winds that, in the Northern Gulf, create an along-Gulf flow (Bordoni and Stevens 2006). The winds are modulated by pulses or surges that originate in cyclonic disturbances over the eastern Pacific tropical warm pool off Central America and propagate northward into the Gulf (Bordoni and Stevens 2006). The monsoon climate of the Gulf thus leads to seasonally reversing winds that affect surface circulation and mixing (Thunnell 1998). From July to October, prevailing winds blow from the southeast. During winter/spring (December through May), prevailing winds blow from the northwest along the Gulf's axis, with speeds that can reach 8 to 12 m s^{-1}. These winds produce strong upwelling along the eastern coast of the Gulf, including in the Northern Gulf, and around all of its islands, although occasional shifts to westerlies tend to dampen upwelling along the Sonoran coast (Roden 1964, Álvarez-Borrego and Lara-Lara 1991, Bray and Robles 1991). Winter winds create the strongest upwelling, whereas strong water-column stratification reduces upwelling during the hottest summer months (Santamaría-del-Ángel et al. 1999).

The winter/spring northwesterlies bring cold dry air from the western continental U.S., causing local cooling of the shallow Upper Gulf. During the rest of the year, the shallow regions of the Upper Gulf are warmer than the offshore waters. This sea surface temperature pattern corresponds to the ground-level air temperature pattern. Winter/spring upwelling brings cooler waters to the surface, and this is seen around all of the islands in the Gulf, including in the Northern Gulf where these upwelled waters mix horizontally to lower sea surface temperatures over the region. Year-round strong tidal mixing and turbulence causes an effect similar to constant upwelling around the larger islands in the Gulf (Hidalgo-González et al. 1997, Lluch-Belda et al. 2003). Thus, like many other subtropical coastal regions of the world, the Northern Gulf is highly seasonal, with sea surface temperatures reaching 31°-32° C in August and September, and dropping to 15°-17° C in January and February (Lavín et al. 1998, Ramírez-León et al. 2015). Coastal and shallow onshore temperatures typically exceed these extremes. These more recent temperature observations do not differ from those made in the 1970s (e.g., Thomson and Lehner 1976).

Many of the broad oceanographic features of the Gulf are imposed by the Pacific Ocean (Lavín and Marinone 2003) that the Gulf communicates with through a ~200 km wide and ~2700 m deep entrance. And, much of the general circulation of the Gulf can be modeled as Kelvin-like internal waves of annual period forced by the Pacific (Beier 1997, Ripa 1997). Surface drifter studies have confirmed the presence, for most of the year, of a northward coastal current on the shelf and slope of the mainland side of the Gulf (Lavín et al. 2014). For much of the year the mean speed of this coastal current is ~0.30 m/s. In contrast, on the western side of the Gulf recirculating currents dominate surface circulation due to mesoscale eddies. For three to four weeks, in June-July, the mainland coastal current is enhanced to a mean speed of ~0.60 m/s, with maximum speeds of ~0.80 m/s (Lavín et al. 2014). In the study by Lavín et al. (2014), one drifter moved from the mouth of the Gulf ~1000 km to the delta in this current in just 20 days.

Surface flows in the Midriff Islands Region (Figure 1) are intense, due to large tidal flows through narrow passages and the exchange of water between the northern and southern regions, and consequently this region is distinguished by intense tidal mixing (Argote et al. 1995, Beier

1997, Lluch-Cota and Arias-Aréchiga 2000, Mateos et al. 2006). A deep, cold, branching flow typically moves north in the Midriff Island Region, with one branch flowing toward the Canal de Ballenas-Salsipuedes Channel over the San Lorenzo Sill, and the other flowing over the San Esteban Sill. The latter surrounds Isla Ángel de la Guarda and converges with the other branch in the Canal de Ballenas-Salsipuedes Channel, thus producing a persistent upwelling in the channel (López et al. 2006, 2008, Marinone 2007, 2008). Marinone (2007, 2008) showed that deep inflows at both ends of the channel result in persistent upwelling that creates the coldest sea surface temperatures in the Gulf.

The principal surface circulation of the Northern Gulf consists of a cyclonic (counterclockwise) gyre in the summer (June to September), and a weaker anticyclonic (clockwise) gyre from November to March (Beier 1997, Lavín et al. 1997, Beier and Ripa 1999, Martínez-Diaz-de-León 2001, Palacios Hernández et al. 2002, Carrillo et al. 2002). As a result, Colorado River deltaic sediments are transported to accumulate in deeper waters to the south of the delta, and also to the west where they create a gently sloping coastline north of San Felipe, Baja California. On the Sonoran side of the Northern Gulf, a submarine channel extends to the 200 m-deep Wagner Basin where many deltaic sediments ultimately end up. At a larger scale, the strong winter-spring northwesterlies result in a net transport of surface waters out of the Gulf and into the open Pacific, whereas the generally weaker summer-fall southeasterlies allow Equatorial Pacific surface waters to penetrate into the Gulf all the way to its uppermost reaches (Bray and Robles 1991, Thunnell 1998, Lavín et al. 2014).

The long, narrow shape of the Gulf of California creates a "bathtub effect." The tidal range (amplitude) is very small at the center "nodal point" (near Guaymas), and increases northward and southward from the center, like water sloshing back and forth in an elongate trough. The tidal range is greatest in the narrow, shallow Upper Gulf where water from each tidal flow piles up higher, like in a fjord. The Upper Gulf is thus a highly tidal region, with a maximum tidal range (lowest low to highest high) of approximately 10 m (33 ft) (Matthews 1969, Grijalva-Ortiz 1972, Stock 1976).

The earliest Spanish explorers in the Upper Gulf (e.g., Ulloa, Alarcón, Nuño de Guzmán, Consag, Ugarte) commented on the Gulf's frequent reddish-colored waters which, in the central and southern regions were later shown to be due to large phytoplankton blooms that spoke to its high productivity (Streets 1878, U.S. Hydrographic Office 1887, Sykes 1937). And even though the muddy reddish waters of the Colorado River Delta (the source of the name "Vermillion Sea") visibly mask such blooms, studies have shown that large plankton blooms also occur in the Upper Gulf, and intense outbreaks of dinoflagellates have been recorded there since at least the 1960s (Brinton et al. 1986). Most of the red silt of the Colorado River Delta originated in the Little Colorado and San Juan River tributaries, which are notable for their red silt load that, prior to the construction of Hoover Dam, was carried all the way to the Gulf (Sykes 1937).

Since the first oceanographic research accomplished in the Gulf of California, in the 1920s and 1930s, it has been recognized as one of the most productive marine ecosystems in the world (Gilbert and Allen 1943). In fact, today it is ranked as a Class I "highly productive ecosystem (>300 g C m^{-2} yr^{-1})" based on global SeaWiFS primary productivity estimates, and one of the five marine ecosystems with the highest productivity in the world (Enríquez-Andrade et al. 2005). It is a eutrophic sea with phytoplankton production on the order of >1 g C m^{-2} day^{-1} to >4 g C m^{-2} day^{-1} (Álvarez-Borrego and Lara-Lara 1991, Santamaría-del-Ángel et al. 1994a,b, Gaxiola-Castro et al. 1995, Thunnell 1998).

The high productivity of the Gulf generates 40% to 50% of Mexico's total fisheries production and supports over 50,000 jobs (Cisneros-Mata et al. 1995, 2010, Cinti et al. 2010, Erisman et al. 2011, 2015, Lluch-Belda et al. 2014), the largest producer in the country being the state of Sonora (Lluch-Belda et al. 2014). And the Northern Gulf is the most important region in all of Mexico in terms of fisheries production, where 77% of the inhabitants are involved in fishing activities and thousands of small, artisanal-fishing boats (*pangas*) use gillnets to harvest blue shrimp (*Litopenaeus stylirostris*), Gulf corvina (*Cynoscion othonopterus*), Gulf (or bigeye) croaker (*Micropogonias megalops*), Spanish mackerel (*Scomberomorus concolor*), and smaller volumes of sharks, rays, and shellfish (INEGI 2000, Rodríguez-Quiroz et al. 2010, Erisman et al. 2015). The three finfish species are all spring spawners in the Northern Gulf and fishing targets their spawning season (Erisman et al. 2015). The average, annual, reported fish catch in the Northern Gulf, 2001-2005, was 18,326 metric tons, targeting an estimated 80 primary species (Erisman et al. 2011, Munguía-Vega et al. 2014). However, it is estimated that Mexico's reported fisheries catch is only about half the actual catch, due to unreported numbers (e.g., illegal catch, bycatch, etc.) (Cisneros-Montemayor et al. 2013). As of 2010, the Gulf corvina catch far exceeded all others in weight, but shrimp exceed all others in dollar value (Rodríguez-Quiroz et al. 2010). Virtually all of the Northern Gulf *panga* fishers target Gulf corvina, and 93% of them also target shrimp (Rodríguez-Quiroz et al. 2010).

There have been several attempts to model the ecosystem of the Northern Gulf, mainly using the Ecopath modeling software (Morales-Zárate et al. 2004, Lercari 2006, Lercari et al. 2007, Lercari and Arreguín-Sánchez 2009). These have concluded that reducing fishing pressure would increase fisheries stocks and reduce the risk to endangered species such as totoaba (*Totoaba macdonaldi*) and vaquita porpoise (*Phocoena sinus*). Lercari and Arreguín-Sánchez (2009) built an ecosystem model for the Northern Gulf that suggested a viable fishing strategy to protect totoaba and vaquita required a decrease in the industrial shrimp fleet (35-

65%), a decrease in the gillnet fleet (52-57%), and an increase of the artisanal shrimp fishery (63-222%) if appropriate fishing methods were to be employed. Morales- Zárate et al. (2004) compared their Northern Gulf model to five other coastal models in Mexico, suggesting a “higher energy use” in the Northern Gulf ecosystem, and that the region has a “highly dynamic, more complex, and probably a more mature ecosystem” than the others.

Álvarez-Borrego (2001) noted that, “Since the times of early explorers the Gulf of California has been described as an area of high fertility, owing mainly to tidal mixing and upwelling processes.” Cummings (1977) reported zooplankton volumes in the Gulf of California exceeded by a factor of two the values reported by Cushing (1969 in Cummings *op. cit.*) for upwelling regions such as Costa Rica or Peru. Although shelf seas are globally a sink for atmospheric CO_2 (Páez-Osuna et al. 2016), productivity is so high in the Gulf of California that Rodriguez-Ibañez et al. (2013) estimated it is likely a net source of carbon, in the form of CO_2, to the atmosphere. Zeitzschel (1969) recorded rates of primary productivity that were two to three times greater in the Northern Gulf than rates in the open Atlantic or open Pacific at similar latitudes. Hernández-Ayón et al. (1993) and Cupul-Magaña (1994), using data since 1989, reported higher nutrient concentrations (NO_2^-, NO_3^-, PO_4^{3-}, SiO_2) in the delta region than reported for most estuarine and non-estuarine marine environments around the world. Prehistorically high primary productivity in the Gulf of California is recorded in biogenic sediments from throughout the Holocene, and productivity rates have remained high for the past 2500 years (Douglas et al. 2007, Staines-Urías et al. 2009).

Increased primary productivity in the Central and Southern Gulf has frequently been shown to be associated with ENSO events, however, this effect is not seen uniformly throughout the Gulf (Santamaría-del-Ángel et al. 1994b, Thunnell 1998, Kahru et al. 2004). It appears that the ENSO signal can be masked in the Central and Northern Gulf by strong tidal mixing and upwelling (Álvarez-Borrego and Lara-Lara 1991, Santamaría-del-Ángel et al. 1994a, Herrera-Cervantes et al. 2010, Páez-Osuna et al. 2016).

Numerous studies in the Gulf have examined primary productivity in the Northern and Upper Gulf, and *all* have shown the region to be highly productive for as far back as published records exist and continuing into the present (e.g., Allen 1923, 1937, 1938; Gilbert and Allen 1943; Zeitzschel 1969; Cummings 1977; Hernández-Ayón et al. (1993); Cupul-Magaña (1994); Millán-Núñez et al 1999; Lluch-Cota and Arias-Aréchiga 2000; Pérez-Arvizu et al. 2013; Rodriguez-Ibañez et al. 2013). Zeitzschel (1969) noted that productivity in the Gulf is comparable to such areas as the Bay of Bengal and the upwelling areas off North Africa and the western coast of the Baja California Peninsula.

The shallow waters of the Northern Gulf are constantly churned by extreme tides, strong winds, and upwellings to create the most productive region in the entire Gulf. In the Northern Gulf, tidal mixing and turbulence occur year round, advecting nutrients into the mixed layer and generating high productivity (Douglas et al. 2007). Surface nutrient concentrations in the Northern Gulf may be as high as 1.0 μM PO_4, 4.0 μM NO_3, and 18 μM H_4SiO_4 (Álvarez-Borrego et al. 1978). Chlorophyll concentration and phytoplankton productivity peak in March and April, and decline to their minima in August and September (Álvarez-Borrego et al. 1978, Hernández-Ayón et al. 1993). The most abundant phytoplankton of the Northern Gulf are diatoms (*Thallassiosira*, *Nitzschia*, *Coscinodiscus*, *Thallassionema*) and dinoflagellates (*Gymnodinium*, *Prorocentrum*) (Millán-Núñez et al. 1999). The main mechanisms and sources of fertilization in the Northern Gulf are: water exchange with the open Pacific (most influx from the Pacific is nutrient-rich deeper waters), upwelling along coastlines and around islands, mixing by tidal currents and turbulence, thermohaline circulation that moves intermediate waters into the mixed layer, coastal-trapped waves, input of anthropogenically derived nitrates and silicates from farming on the Colorado River Delta, and erosion of ancient Colorado River sediments (Cupul-Magaña 1994, Argote et al. 1995, Lavín et al. 1995, Gaxiola-Castro et al. 1999). Decomposition of plant matter from halophytes growing on the vast region of the lower delta (visible in Figure 2 as the brown region below the bright-green agricultural fields of the upper delta) no doubt also contributes to high nutrient levels in the Upper Gulf, although there are no estimates of the magnitude of this contribution.

The Upper Gulf has some of the highest nutrient and chlorophyll-*a* concentrations of any of the world's seas (e.g., Álvarez-Borrego et al. 1978, Hernández-Ayón et al. 1993), and the Upper Gulf and Midriff Islands region (Islas Ángel de la Guarda and Tiburón, and their associated smaller islands, Figures 1 and 2) consistently show the highest productivity levels of the entire Gulf of California (e.g., Álvarez-Molina et al. 2013, Pérez-Arvizu et al. 2013, Ulate et al. 2016). Cortés-Lara et al. (1999) found chlorophyl maxima in the Midriff Islands region an order of magnitude larger than in surface waters at the mouth of the Gulf. High primary productivity in the Upper Gulf is shown by chlorophyll-*a* concentrations reaching 18.2 mg m^{-3} and averaging 1.8 mg m^{-3} (1997-2007; Pérez-Arvizu et al. 2013). Ulate et al. (2016) showed the Northern Gulf to consistently have higher productivity than the Central or Southern Gulf (annual average 1.7 mg m^{-3}, 1998-2010). As shown by Millán-Núñez et al. (1999) and Morales-Zárate et al. (2004), chlorophyll and primary productivity values in the Upper Gulf indicate that it is an area with high autotrophic productive potential, able to maintain a large food chain where there is no freshwater input. There also appear to be no records of severe hypoxia in the Northern Gulf (Lluch-Cota et al. 2010), which is consistent with the high level of mixing in the region.

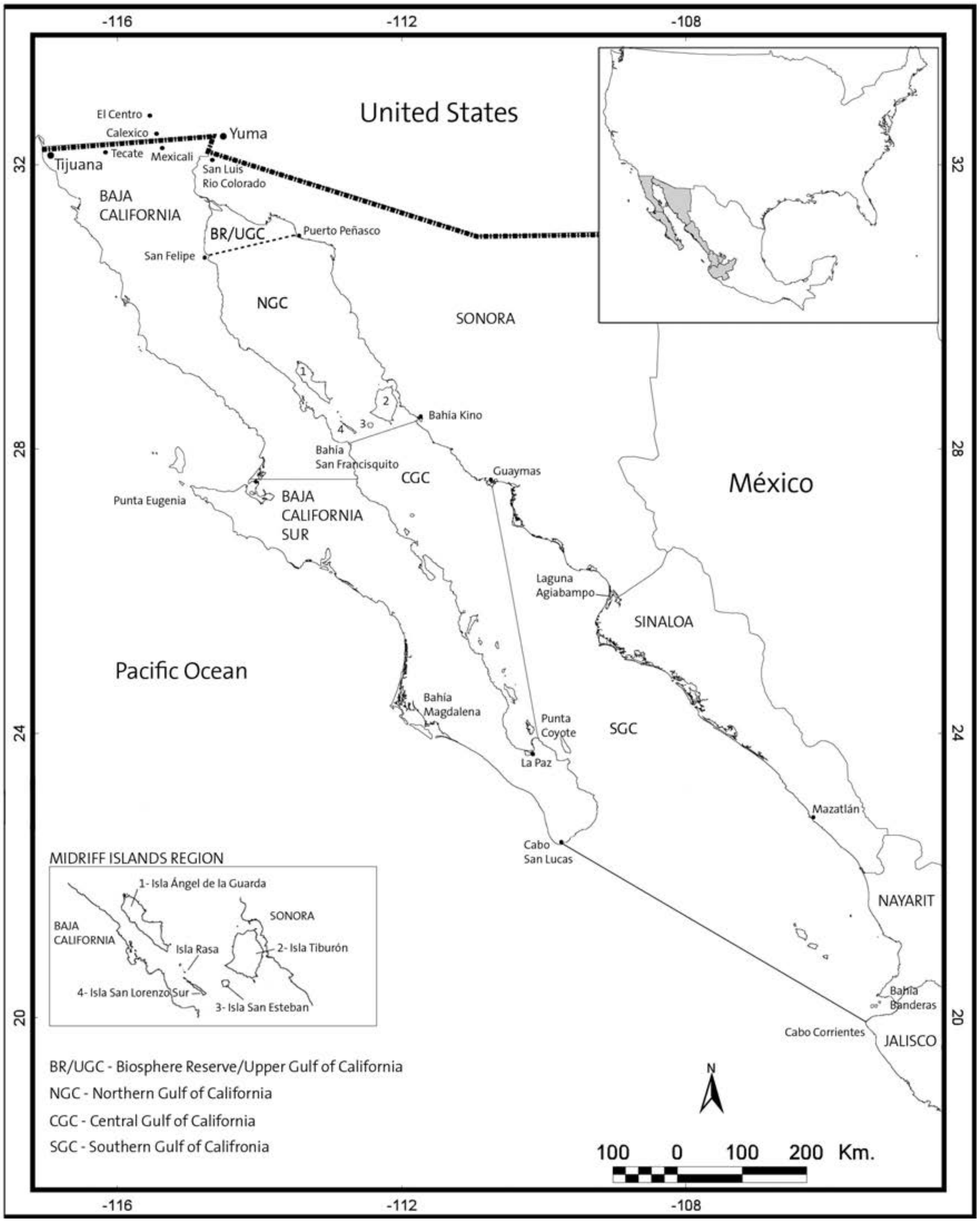
In addition to having high nutrient levels and primary productivity, the Gulf is also biologically diverse, harboring about 6000 described animal species, over 2800 of which (including over 130 endemic species) inhabit the Northern Gulf (Brusca et al. 2005, Brusca 2007, 2010, Herrera-Valdivia et al. 2015, Brusca and Hendrickx 2015).

I am not aware of any published work providing evidence that a decrease in Colorado River inflow has reduced primary productivity in the Upper Gulf. One direct way to test this hypothesis is to track productivity and river flow over multiple-year time periods, to see if there is a correlation. At least two studies have done this. Nieto-García (1998) compared nutrient levels in the Upper Gulf during one of the largest known post-dam high-river excess flow periods (spring 1993) and a zero-flow period (spring 1996) and found that NO_3 and PO_4 concentrations were actually lower in the flow year (1993). And, when she compared chlorophyll (from in-situ sampling) between the two periods there were no significant differences (Table 1). A 26-year study (Ramírez-León et al. 2015) of satellite-measured chlorophyll in the Northern Gulf also found no statistical relationship between Colorado River inflow and productivity, and found no increase in productivity during the wettest years. In fact, Ramírez-León et al. (2015) found chlorophyll levels actually dropped in the Northern Gulf during the blockbuster El Niño winters of 1983-1984 and 1997-1998, in comparison to those of 1981-1982 and 1999-2000, respectively, suggesting this drop in primary production could have been due to depressed salinities resulting from higher Colorado River flows during those ENSO years.

Seasonal productivity of the Gulf was documented by Thunnell (1998) using sediment traps in the Guaymas Basin. He found late fall-spring sediment deposits dominated by plankton (biogenic sediments) and summer-early fall sediments dominated by lithogenic material (a mix of eolian transport and river runoff, the former being the main contributor). Measureable river runoff is largely due to the summer monsoon rains, which concentrate on the western flanks of the Sierra Madre Occidental ranges to the east, bringing limited fluvial sedimentation to the Gulf (Douglas et al. 2007). Thunnell (1998) characterized this pattern as a direct response to the seasonally reversing monsoon climate, and Thunnell et al. (1994) noted that the diatom production of the Gulf is one of the highest in the world. In the Central Gulf, diatom skeletons can account for 75% or more of the total flux to the benthos (Thunnell 1998). The summer monsoon rains are the main source of water in northwest Mexico, providing 70% of the annual rainfall and 80% of the surface runoff (Douglas 1995, Anderson et al. 2000, Páez-Osuna et al. 2016). Summer monsoon conditions in the Gulf were probably established at least 6000 years before present (González-Yajimovich et al. 2007).

Currently, with lack of direct Colorado River flow to the Gulf of California (and overall high evaporation rates), the Upper Gulf is the equivalent of an inverse (negative) estuary. Like all inverse estuaries, salinity increases toward the head throughout the year. North of the Midriff Islands the Gulf is shallow (mostly <150 m depth) and well mixed vertically throughout most of the year. As with other inverse estuaries in arid regions of the world, the increasing salinity, and thus density, toward the head leads to pressure gradients, water-mass formation, and sporadic gravity currents in both winter and summer (Lavín et al. 1998). Thus, evaporation and increased salinity throughout the Gulf lead to the formation of dense “Gulf Water” which sinks and flows southward (Bray 1988). Gravity currents tend to occur when the tides and winds are at their weakest. Water is most dense from December to February when the high-salinity water sinks beyond 200-m depth, whereas in summer it reaches depths of only 20-30 m (Carriquiry et al. 2001). The high-salinity water found in winter at the bottom of the Northern Gulf’s Wagner Basin comes from the Upper Gulf, including the large Bahía Adair, having reached there by gravity currents. Indirect evidence suggests that the most extensive gravity currents form in October and November, and this is likely when the relatively hypersaline surface waters of the Upper Gulf move into mid-depth layers as the water cools (Bray 1988, Lavín et al. 1998).

Key studies on Northern Gulf oceanography, since 1974, include: Álvarez-Borrego and Galindo-Bect 1974; Álvarez-Borrego et al. 1975; Álvarez-Borrego and Schwartzlose 1979; Bray 1988; Álvarez-Borrego and Lara-Lara 1991; Lavín et al. 1995, 1997a,b, 1998; Nieto-García (1998), Lavín and Sánchez 1999; Soto-Mardones et al. 1999; Martinez-Diaz-de-León 2001; Álvarez-Borrego 2001, 2002; Álvarez and Jones 2002; Carrillo et al. 2002; Palacios-Hernández et al. 2002; Lluch-Cota et al. 2007; and Ramírez-León et al. 2015.



The Gulf of California, showing some geographic place names mentioned in the text (map copyright R. C. Brusca)

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 (the single supercontinent that preceded Pangaea, 1 billion years ago). Sitting on the southwestern edge of the great Laurentian Craton, these ancient rocks record a geological history that predates the breakup of Rodinia ~750 Ma. The Puerto Blanco Formation near Pitiquito, northern Sonora, and the its underlying La Ciénega Formation, contain fossils that identify the location of the Ediacaran/Cambrian boundary in Mexico, and thus the position of Laurentia during the onset of the Cambrian. These fossils include the Cambrian index fossil *Treptichnus pedum* (Puerto Blanco Formation) and the Neoproterozoic index fossil *Cloudina* (La Ciénega Formation). *Treptichnus pedum* is a trace fossil representing the onset of burrowing behavior in Metazoa, and it is used to define the location of the Ediacaran/Cambrian boundary throughout the word.

ENDNOTE 16. Among the Sky Islands of southeastern Arizona and northeastern Sonora, ancient and massive granite batholiths are exposed on mountain slopes. These show a great range of composition, color, inclusions, etc. In the Santa Catalina Mountains, next to Tucson, at least three distinct types of granite can be seen. On the north and west sides of the range, 1.4 billion-year-old Oracle Granite predominates. It can be recognized by the presence of large (up to 2 cm) feldspar crystals—seen in the two photographs below. The feldspar is harder than the rest of the rock, and over time as this granite decomposes, there is nothing left but a pile of feldspar crystals. The rocks in these photos also happen to contain large (to 30 cm), dark, mafic inclusions. During the formation and slow cooling of the magma (which allows for the unusually large feldspar crystal growth), pieces of the magma chamber walls can get incorporated into the cooling magma. These particular inclusions are probably basalt. These dark inclusions also show up in the metamorphosed Oracle Granite in the Santa Catalinas, known as Catalina Gneiss, where they are called *schlieren*.

Two photographs of Oracle Granite from the Santa Catalina Mountains, near Tucson (from Southerland Wash, Catalina State Park). Large white feldspar crystals, typical of Oracle Granite, can be seen and, in these particular rocks, larger dark inclusions that are pieces of the magma chamber wall that became trapped in the magma as it cooled.

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GLOSSARY OF COMMON GEOLOGICAL TERMS

aa. Basaltic lava characterized by a very rough surface that commonly includes broken lava blocks called "clinkers." Aa lavas typically erupt at temperatures of 1000 to 1100°C.

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 the rocks or other objects tested. For example, C^{14} is typically used to date fairly recent events (e.g., biological materials), K/Ar is 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 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. Streambeds 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 predominantly composed 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 seawater 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 to describe 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 in the ground, usually located 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 (hundreds 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, most 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.

coquina. Conglomerates formed from shells.

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.

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. 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. Fragments of material that 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, and 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 (Rivera, 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. An 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, although not always along a fault.

***estero*.** Commonly used word in Mexico for tidally flushed, hypersaline coastal seawater lagoons. When the lagoons are at the mouth of a river, they can be considered “negative estuaries.”

estuary (noun). An area where fresh water comes into contact with seawater, usually in a partly enclosed coastal body of water and usually a river meeting the sea. 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 seawater 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. 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 that 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 seawater and exposed to air.

Intrusive 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. **Intrusion** is the process by which magma is emplaced into other rocks. *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.

kipuka. An area of land surrounded by one or more younger lava flows. A kipuka forms when lava flows around both sides of a hill or ridge (or older lava flow) as it moves downslope or spreads from its source. Like the words aa and pahoehoe, kipuka is a Hawaiian word.

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 Ma and ending ~35-55 Ma, 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.

Ma. Millions of years ago.

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).

mafic. A geological term referring to dark-colored, mainly ferromagnesian minerals such as pyroxene and olivine.

magma. Melted rocks below or within the Earth's crust (adjective - 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 seawater 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 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 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, metaphorically, "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 USGS 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).

pahoehoe. Basaltic lava that has a smooth, billowy, undulating, or ropy surface. These surface features are due to the movement of very fluid lava under a congealing surface crust. Aa lavas typically erupt at temperatures of 1100 to 1200°C. *Cf.* **aa**

Panamanian Seaway (aka Panama Seaway). The open oceanic seaway between the Caribbean Sea/Atlantic Ocean and the Pacific Ocean that ultimately closed either around 3.0 to 2.5 million years ago. 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. The 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. Referring to igneous rocks that are coarse-grained, and 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 seawater (~5.5 Ma) 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. 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. 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. May refer to living or inanimate objects.

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 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 that 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 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. 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. 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**.