Lunar and Planetary Laboratory
Department of Planetary Sciences

¡Viaje a Baja!

(Mexico)

Planetary Geology Field Practicum

PtyS 594a

Spring 1998

The University of Arizona
Tucson, Arizona

Planetary Geology Field Practicum

Baja California Norte, Mexico
28 February - 3 March 1998

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This Guide Book is produced as part of the Planetary Sciences course PtyS 594a - Planetary Geology Field Practicum led by Jay Melosh at the University of Arizona, Tucson, Arizona. Editors: Nancy Chabot and Eric Wegryn

The Planetary Sciences Field Trip Heads South of the Border

Encouraged by the unqualified success of our field trip to Yellowstone National Park last September, (and bolstered by the fact that Jay's last Planetary Surfaces class managed to bring back *all* of their vehicles from Mexico,) this semester we once again expand the range of our field excursions and travel to Mexico to explore the Baja peninsula.

Apart from the obvious lures of sand, surf, and fish tacos, we will have an opportunity to see a region of North America that many of us have never seen before, a region which is somewhat geographically (and culturally) isolated from us.

Some of the targets on this trip will be familiar to us (at least those of us old-timers who have been around here for years), such as Anza Borrego, that freak of nature the Salton Sea, and the ever-popular Pacific shoreline. Also, making an encore appearance due to their great popularity on the Yellowstone trip, we'll see lots of algae and microbial scum.

But perhaps the highlight of this trip will be something new for most of us: a chance to examine the K-T boundary. This thin, iridium-rich stratigraphic layer marks the end of the Cretaceous period, and the beginning of the Tertiary about 65 million years ago. It also marks a significant transition in the fossil record, and hence the evolution of life on Earth. It signaled the end of the big, arguably very ugly, reptilian monsters of the Mesozoic, and the ascension of the nice, furry, friendly mammals that were to become our ancestors.

We will have talks on the likely cause of this important transition, a large impact event, on the effect on the unfortunate* creatures that happened to witness it, and on the ever-debatable theory that this sort of thing happens to Earth fairly regularly every 26 to 30 million years.

In another first, we will be treated on this trip to an animation of plate tectonic movement of the Baja region, presented on a laptop computer which the department has obviously decided it doesn't need any more.

In addition to the usual geology stuff, we will also have supplementary talks on the local vegetation and on satellite navigation, as we cruise in leather-upholstered style through the malpais of Baja Norte. (At least we won't have to worry about getting lost in the middle of nowhere, with our GPS receivers and our resident expert on navigation, Ralph . . . unless of course we somehow get separated from Ralph . . .)

But of course it won't all be leather and iridium. We must be prepared to deal with not only the usual field trip hardships, but also unpredictable assaults by El Niño, banditos, the Federales, and U.S. Customs. So grab those passports and visas, and pack those fire extinguishers well, because we're heading sur de la frontera, to meet our destiny, for better or worse. As the redoubtable Chris Chyba would say, <<*¡Verás en infierno!*>>

Eric Wegryn

* But fortunate of course for all those who survived the cataclysm to feast on roast dinosaur.

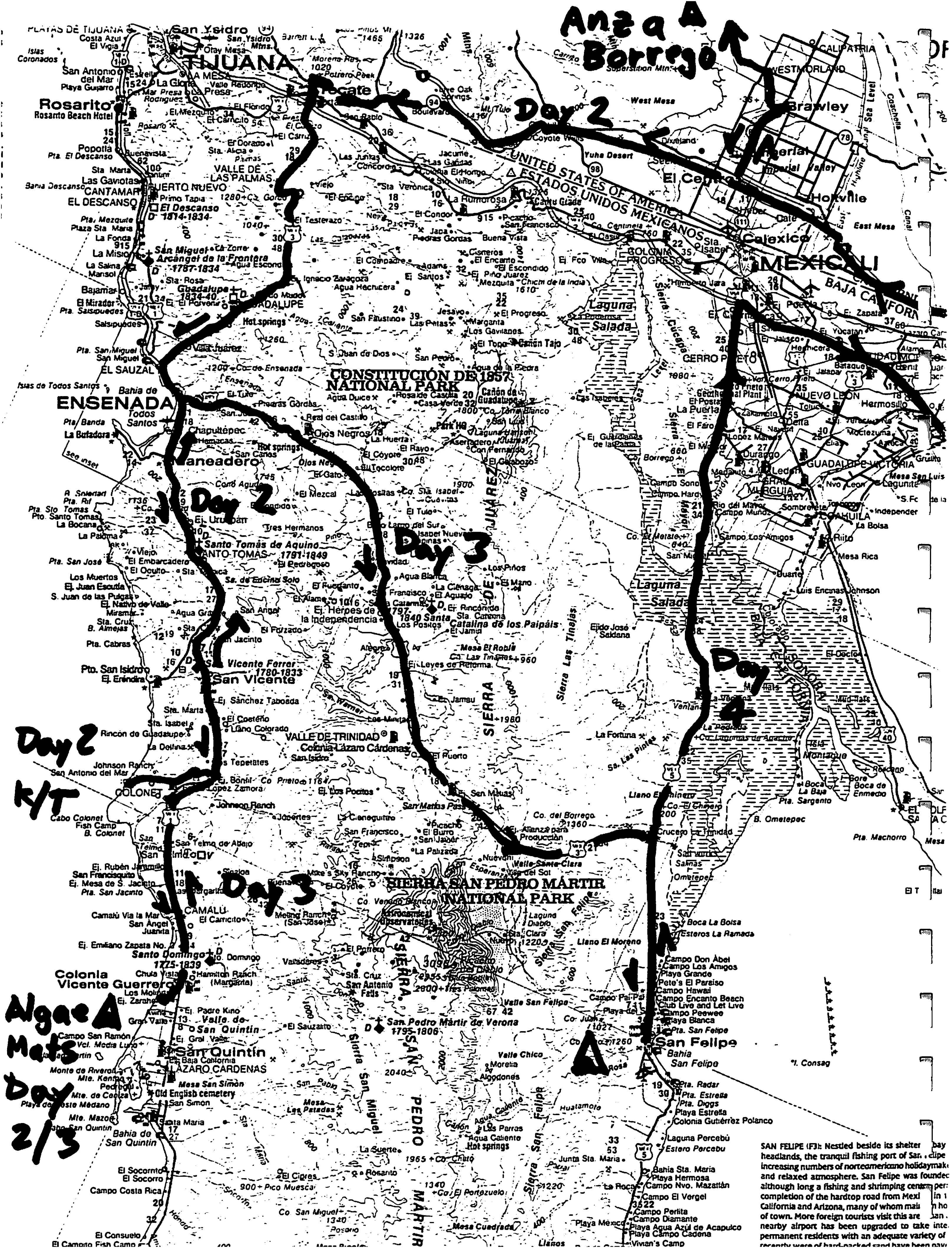
Itinerario / Guía de Viajeros

sábado	8:00 a.m.	Assemble at LPL loading dock, load trucks
28 de febrero	9:05	Depart LPL, head west on Interstate 10, then I-8 (Lanagan, Lorenz)
1998	12:25 p.m.	almuerzo (near Yuma)
	3:09 **PST**	Turn north at El Centro (CA 86) toward the Salton Sea
	3:52	Stop at the Salton Sea (Spitale)
	4:43	Stop at Anza Borrego (Jaeger)
	6:09	Make camp (Anza Borrego) (Emery, Phillips)
domingo	8:04 a.m.	Break camp, return south through lovely Imperial Valley
1 de marzo	9:21	Take I-8 to CA 94 to Tecate, cross border into Mexico
	10:58	Take Hwy. 3 to south Ensenada
	12:13 p.m.	almuerzo
	1:34	Stop at beach (Hurford)
	3:08	Ammonite outcrop (Mastrapa)
	3:33	K-T boundary (Chabot, Grier, Pierazzo, Wegryn)
	6:11	Make camp (Laguna Figeroa)
lunes	8:09 a.m.	Break camp
2 de marzo	8:46	Inspect algal mats (Cohen, Trilling, Head)
	9:24	Head back north to Ensenada on Hwy. 1
	11:18	Take Hwy. 3 to San Felipe (Jaeger)
	12:16 p.m.	almuerzo
	3:43	Play in Golfo de California (Lorenz)
	6:01	Make camp (San Felipe)
martes	8:42 a.m.	Break camp; head north on Hwy. 5 toward Mexicali (Rivkin)
3 de marzo	11:11	Stop at Cerro Prieto Geothermal Field (Fanny)
	11:07 **MST**	almuerzo
	2:19 p.m.	Take Hwy. 2 east to Sonoita, cross border into U.S.A.
	5:59	Return to Tucson

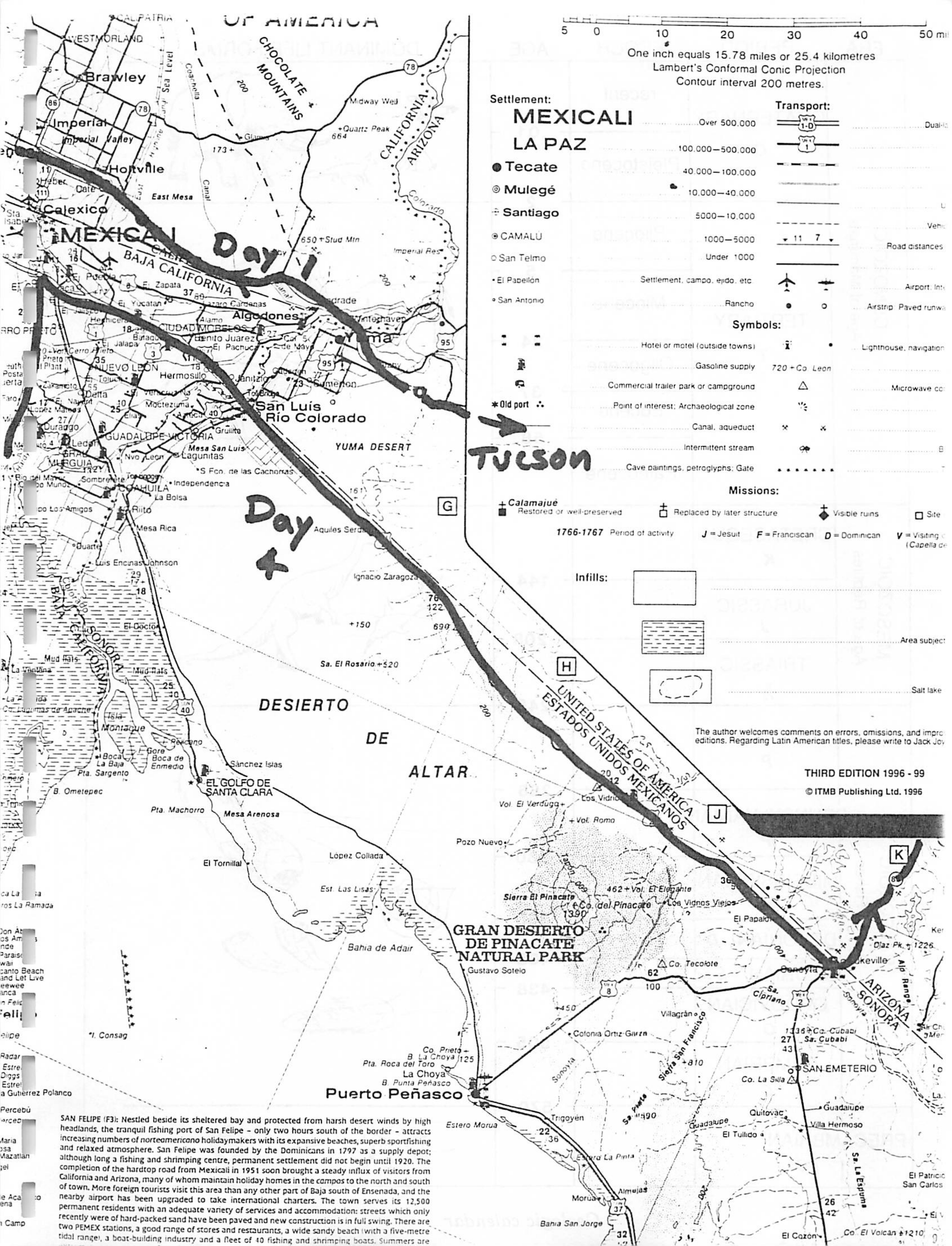
NOTE: Except for beginning and end of trip, times are given in **Pacific Standard Time** (subject to change)

Names in parentheses indicate people who will give talks.

Primary drivers: Barb Cohen, Cynthia Phillips, Andy Rivkin, Joe Spitale, David Trilling, Eric Wegryn



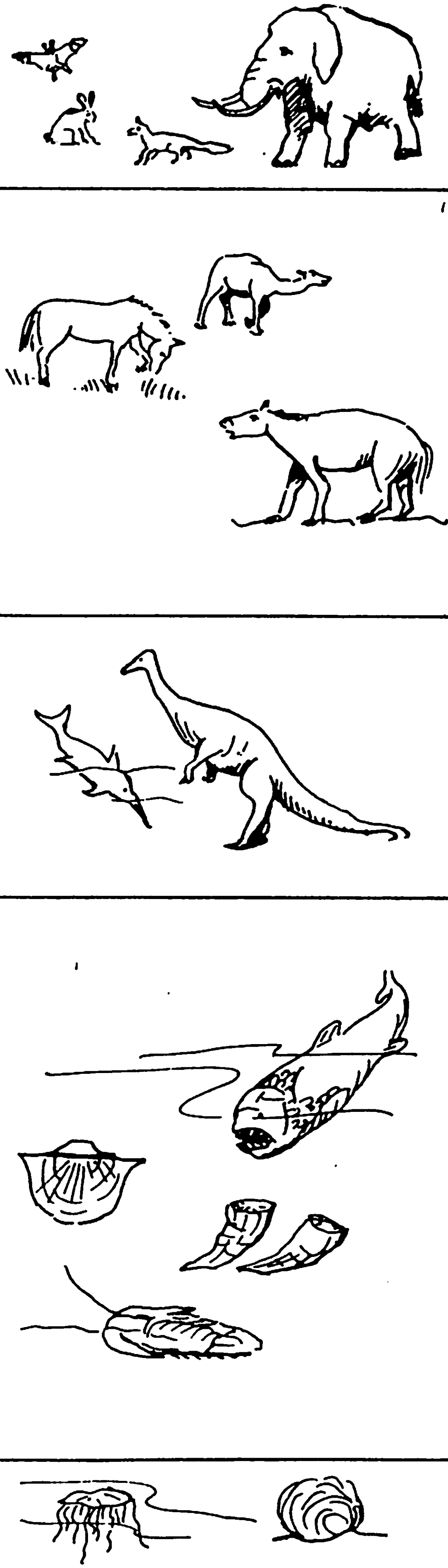
SAN FELIPE (F3): Nestled beside its shelter... bay headlands, the tranquil fishing port of San... elipe increasing numbers of norteamericano holidaymak... and relaxed atmosphere. San Felipe was founde... although long a fishing and shrimping cente... per... completion of the hardtop road from Mexi... in California and Arizona, many of whom mai... n ho... of town. More foreign tourists visit this are... an. nearby airport has been upgraded to take inte... permanent residents with an adequate variety of... recently were of hard-packed sand have been pav...



SAN FELIPE (F3): Nestled beside its sheltered bay and protected from harsh desert winds by high headlands, the tranquil fishing port of San Felipe – only two hours south of the border – attracts increasing numbers of *norteamericano* holidaymakers with its expansive beaches, superb sportfishing and relaxed atmosphere. San Felipe was founded by the Dominicans in 1797 as a supply depot; although long a fishing and shrimping centre, permanent settlement did not begin until 1920. The completion of the hardtop road from Mexicali in 1951 soon brought a steady influx of visitors from California and Arizona, many of whom maintain holiday homes in the *campos* to the north and south of town. More foreign tourists visit this area than any other part of Baja south of Ensenada, and the nearby airport has been upgraded to take international charters. The town serves its 12,500 permanent residents with an adequate variety of services and accommodation: streets which only recently were of hard-packed sand have been paved and new construction is in full swing. There are two PEMEX stations, a good range of stores and restaurants, a wide sandy beach (with a five-metre tidal range), a boat-building industry and a fleet of 40 fishing and shrimping boats. Summers are

ERA	PERIOD	EPOCH	AGE
CENOZOIC Age of Mammals	QUATERNARY *Q*	recent	.01
		Pleistocene	2
	TERTIARY *T*	Pliocene	5
		Miocene	24
		Oligocene	37
		Eocene	58
		Paleocene	66
MESOZOIC Age of Reptiles	CRETACEOUS *K*		144
	JURASSIC *J*		208
	TRIASSIC *T̄R*		245
PALEOZOIC Age of Fishes	PERMIAN *P*		286
	PENNSYLVANIAN *IP*		330
	MISSISSIPPIAN *M*		360
	DEVONIAN *D*		408
	SILURIAN *S*		438
	ORDOVICIAN *O*		505
	CAMBRIAN *C*		570
PRECAMBRIAN *pC*			

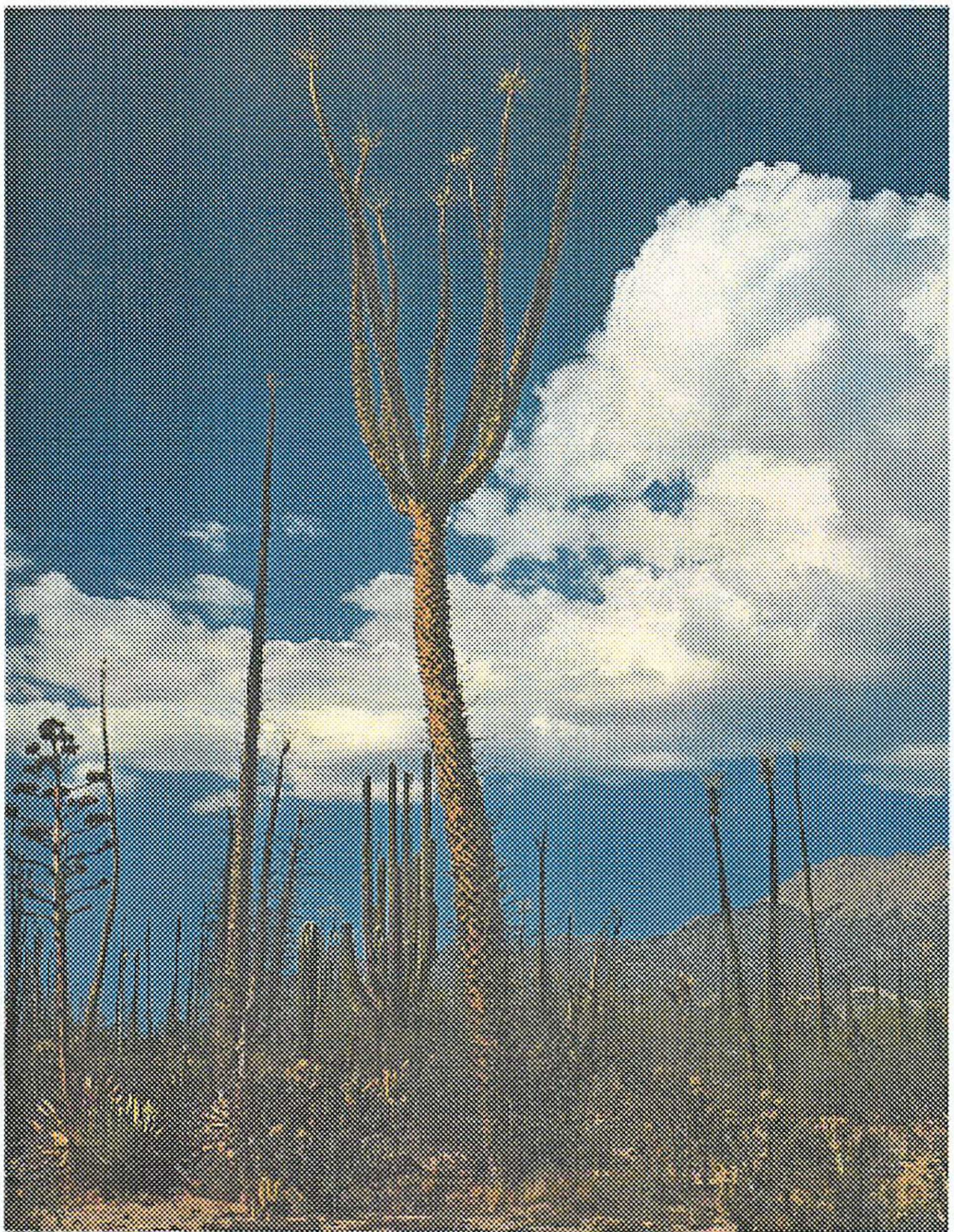
DOMINANT LIFE FORMS



Geologic calendar

Planetary...errr...Plant Sciences Field Trip

Vegetation of Baja California



Boojum Tree
Cirio

Your Gringo Host: Pedro Lanagan

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Delgadillo (1992) - Phytogeographic Maps

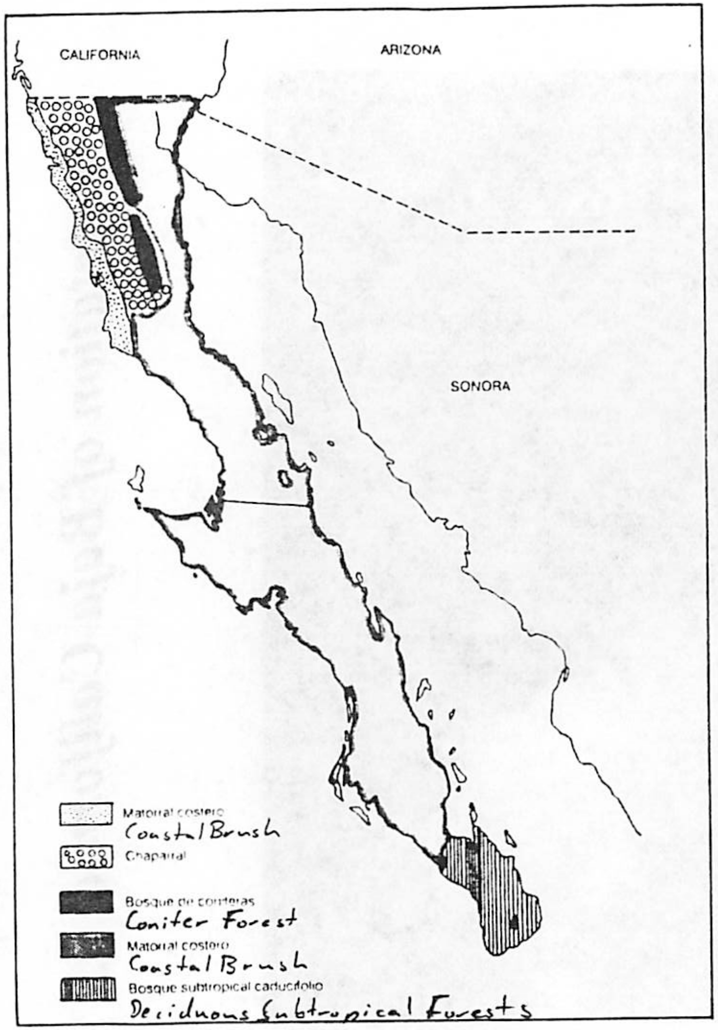

Figura 15a. Principales tipos de vegetación en Baja California.

¡Deal with the Spanish, gringos!

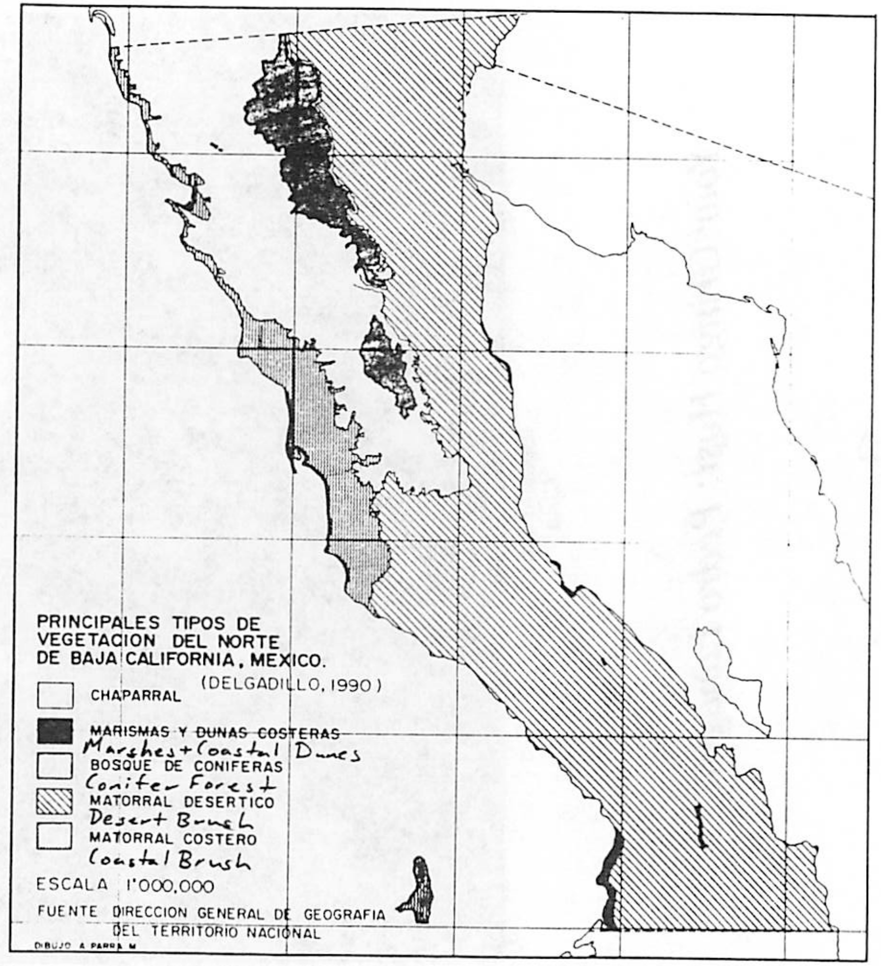

Figura 15b.

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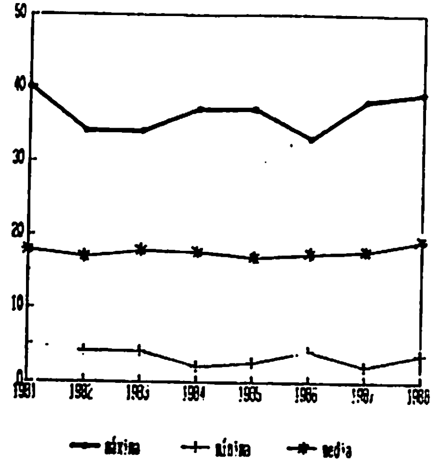
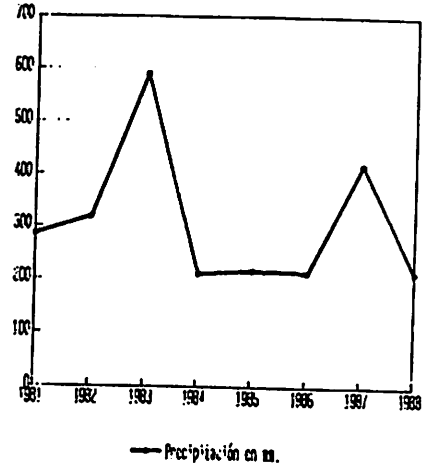
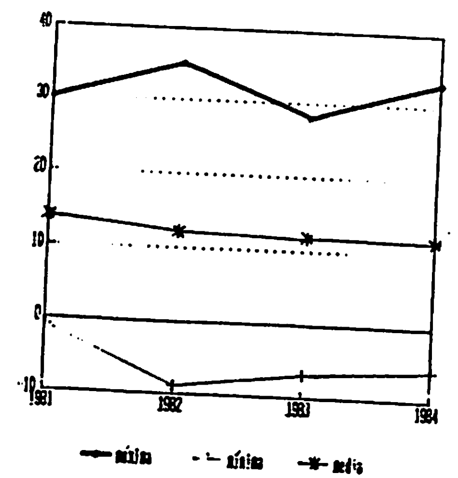
Ensenada, B.C.
Temperatura



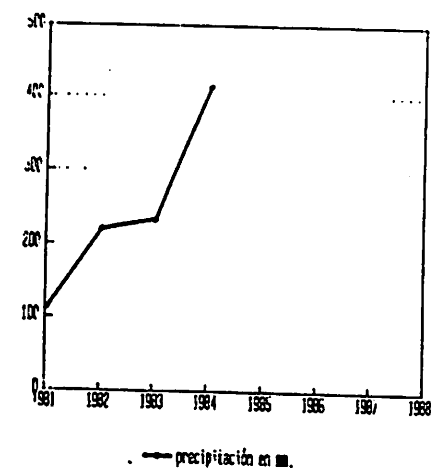
Ensenada, B.C.
Precipitación

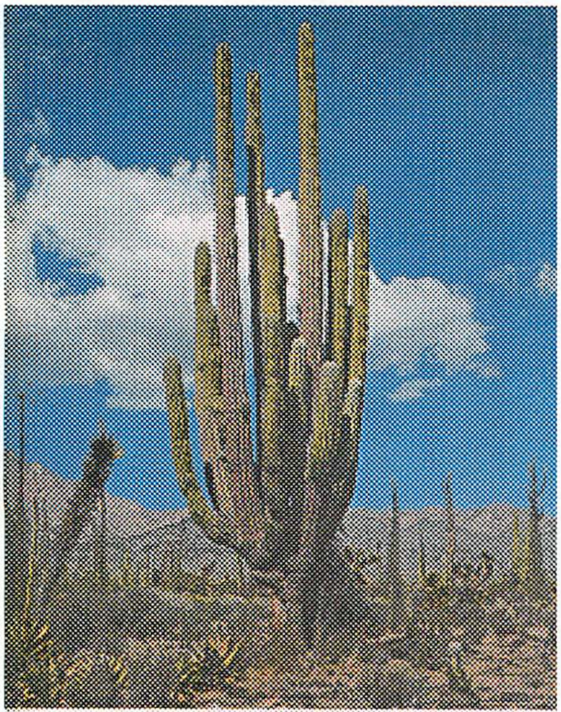


San Pedro Mártir, B.C.
Temperatura

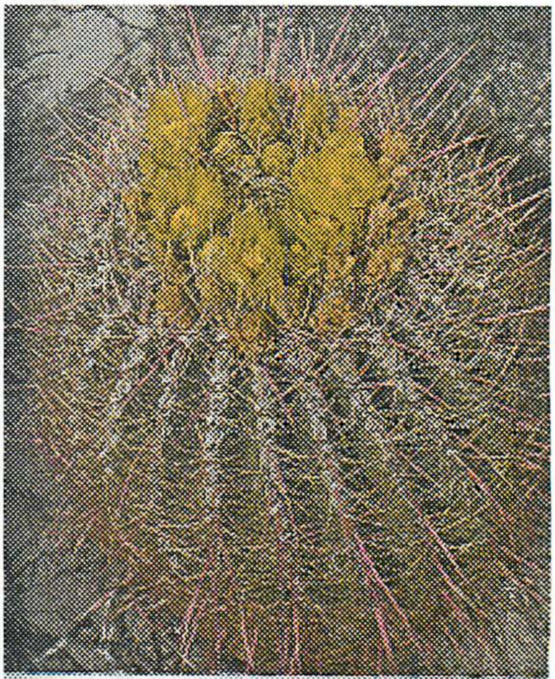


San Pedro Mártir, B.C.
Precipitación

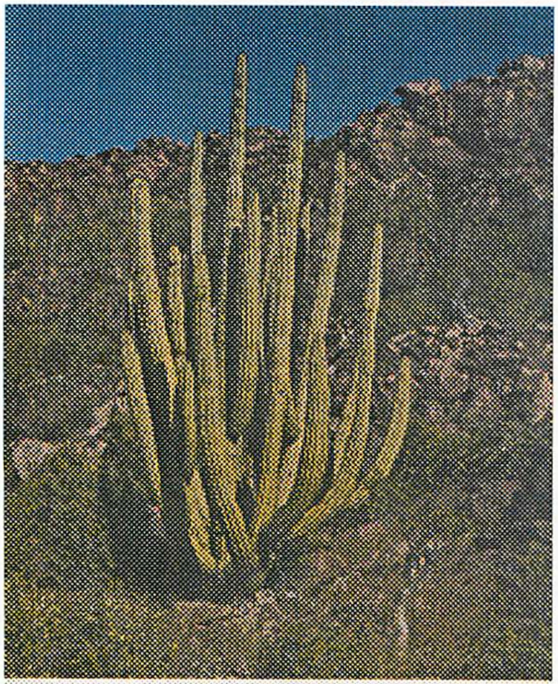




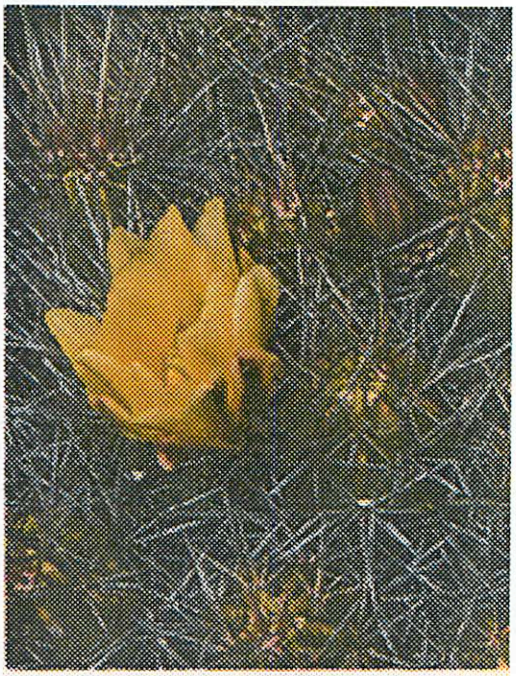
Cardón



Compass Cactus
Biznaga



Organ Pipe Cactus
Pitaya Dulce



Maritime Hedgehog
Pitayita

TABLE 2 Tabulation of families, genera, species, subspecies/varieties, and endemics embraced by the flora of Baja California, by major plant groups

Taxonomic group	Families	Genera	Species	Subspecies/ varieties[a]	Endemics[b]
Ferns and allies	8	22	65	5	4
Gymnospermae	3	6	24	1	1
Dicotyledones:					
Apetalae	25	91	324	41	86
Gamopetalae	38	332	1,040	89	296
Polypetalae	59	290	846	105	267
Monocotyledones:					
Poaceae (Gramineae)	1	86	239	3	3
All others	21	57	167	9	29
Totals	155	884	2,705	253	686

[a] Beyond one per species. *[b] Total endemics in preceding two columns.*

TABLE 3 Eight most heavily represented families of Baja California plants, and percentage of endemics in each

Family	Genera	Species	Subspecies/ varieties[a]	Endemics[b]	Percentage endemic taxa
Compositae	130	405	35	135	30.7
Poaceae (Gramineae)	86	236	3	3	1.3
Leguminosae	55	207	36	74	30.5
Cactaceae	17	91	10	71	70.3
Scrophulariaceae	23	84	4	17	19.3
Euphorbiaceae	19	78	11	27	30.3
Polygonaceae	10	73	12	31	36.5
Brassicaceae (Cruciferae)	28	69	14	13	15.7

[a] Beyond one per species. *[b] Total endemics in preceding two columns.*

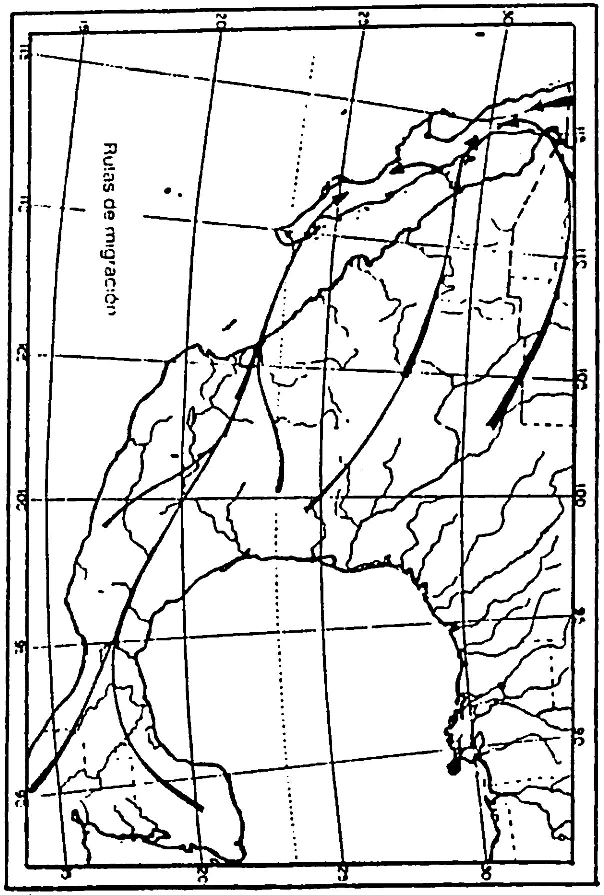
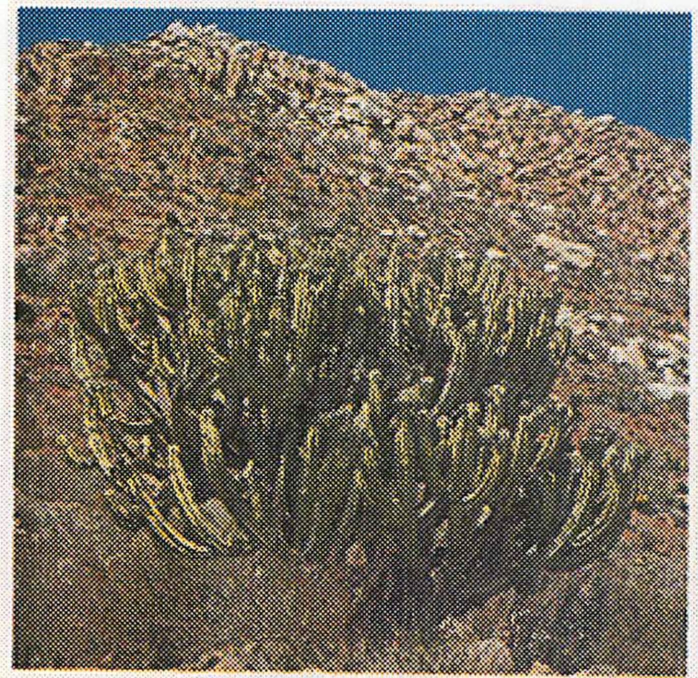
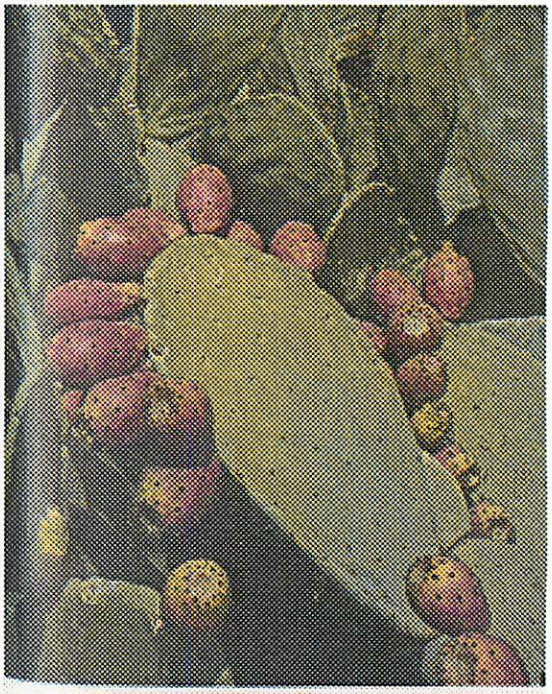


Figura 13. Cuatro principales rutas de migración seguidas por las plantas hacia la península de Baja California, además de varias rutas subsidiarias. (Wiggins, 1960).

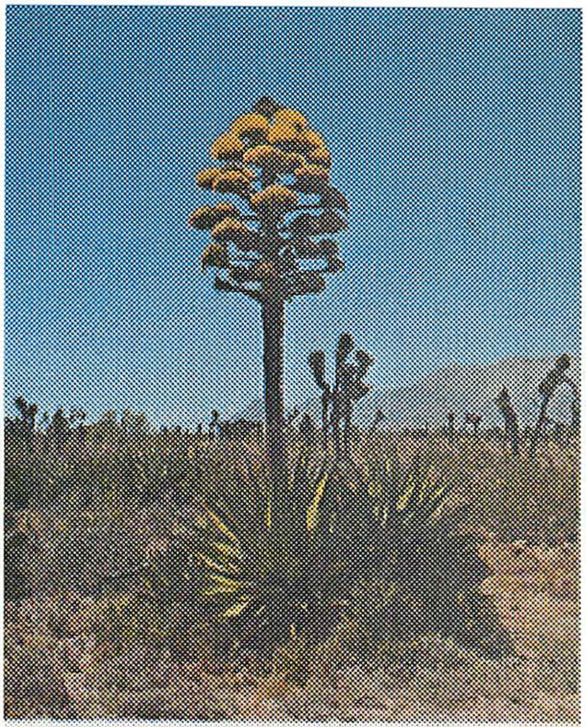


Candelabra Cactus
Cochal



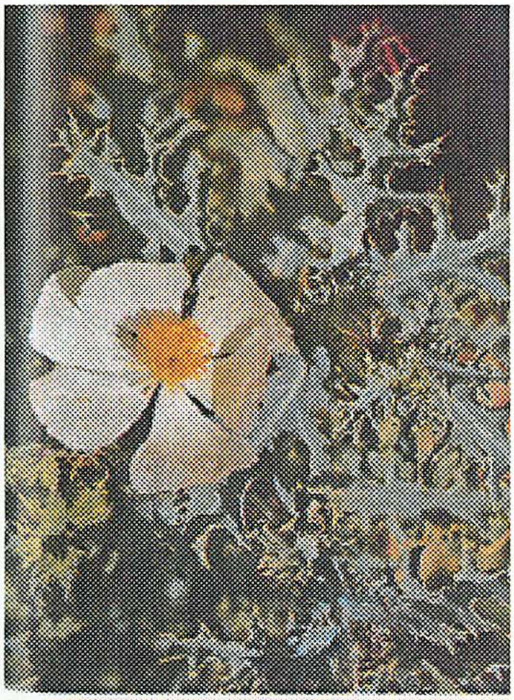
Prickly Pear Cactus
Nopal, Tuna

Wild Rose
Rosa Silvestre

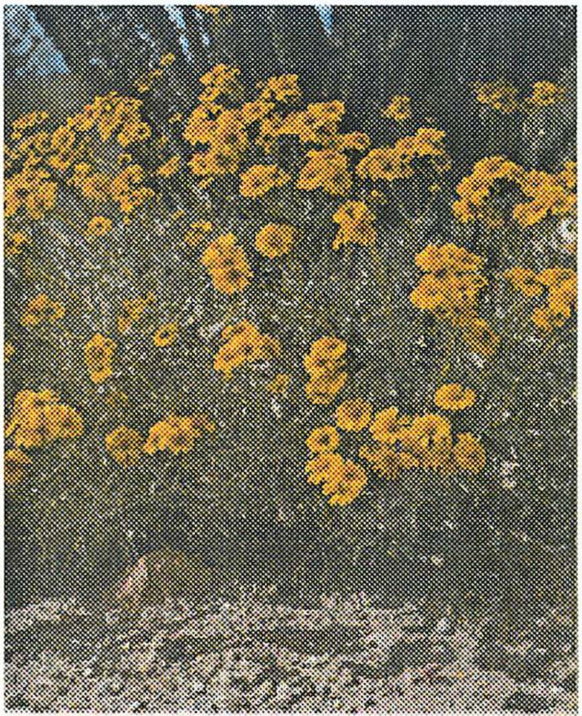


Coastal Agave
Mescal

Arroyo Lupine
Garbancillo



Prickly Poppy
Chicalote



Brittlebush
Inciense

About the Pretty Pictures

The plant album included in this handout is hardly meant to be anything other than a poor sampling of the variety of vegetation we will encounter on this trip. Basically, the photos of plants fall into two general categories: plants that we may see in flower (as such coverage was requested), and cacti that we may see (as they are generally cool for reasons I'll get into later.) I was also biased towards those species which are either endemic to Baja California or have some associated neato stories. Clearly, this shortchanges the coniferous plants of the higher elevations, the vegetation of estuaries, residents of coastal dunes, etc. Rest assured, I will cover these at the appropriate times.

Oh yes...we probably will be just a bit too far north to see cirios like the one shown on the title page. However, I have (unjustified) hopes that maybe they have a range larger than the guide books indicate.

Selected References

Delgadillo Rodríguez, José. 1992. *Florística y ecología del norte de Baja California.* Universidad Autónoma de Baja California. Ensenada.

Roberts, Norman C. 1989. *Baja California Plant Field Guide.* Natural History Publishing Co. La Jolla.

Turner, Raymond M., Janice E. Bowers, and Tony L. Burgess. 1995. *Sonoran Desert Plants: An Ecological Atlas.* University of Arizona Press. Tucson.

Wiggins, Ira L. 1980. *Flora of Baja California.* Stanford University Press. Stanford.

SATELLITE NAVIGATION

Hitch your Wagon to a Star

Ralph Waldo Emerson

The Prudent Navigator will not rely solely on any single aid to navigation

US Coast Guard Notices to Mariners

must.....talk.....about....rockets and planes and stuff

Ralph Lorenz

Really Early Satellite Navigation

While latitude could be easily determined on a ship using the sun and a sextant, the problem of determining longitude was a significant problem, prompting the Engish government (dependent on maritime navigation for its strategic survival and commercial success) in 1714 to offer a prize of some 20000 pounds for its solution. The difficulty was that no-one had devised a clock that could keep sufficient accuracy on an ocean voyage to allow star fixes to be made.

One proposed idea (Whiston, 1738) was to use the relative configuration of the Galilean satellites observed through a small telescope to determine time. This fell afoul, however, of the difficulties of using a telescope on a heaving deck.

Ultimately the issue was solved by making the clock small. Harrington's chronometer kept time within a minute or so during a crossing of the Atlantic, and used bimetallic components (to compensate for thermal expansion) and had two oppositely-swinging balance wheels to null the effect of the ship's motion. He was awarded the prize a mere 3 years before his death, some 40 years after his clocks first met the Board of Longitude's success criteria. The story was a recent UK best seller (Sobel, 1995) and is also told elsewhere (e.g. Smiles, 1884).

The Modern Era - Radio Navigation

While commerce (albeit strategic commerce) was the driver for early navigation, the next steps were prompted by the need for night-time bombing raids during World War 2. By flying along a radio beam, and timing the release of bombs by a number of cross-beams, German bombers could improve their night accuracy to about 120 yards. The system, however, proved vulnerable to British jamming.

Peacetime systems for general navigation (LORAN-C) use a 'master station' emitting pulses; secondary stations emit other radio pulses when they receive the master pulses. A navigator can use the time difference between his/her receipt of the master and two slave pulses to determine his/her location (exercise for the reader: prove that the curves of constant time difference, on a flat Earth at least, correspond to hyperbolae). A similar system, DECCA, operates over a smaller region (European waters) with correspondingly higher accuracy.

Other systems (RDF - radio direction finding) use rotating beacons : from the timing of the signal, the bearing from the beacon is known.

The First Satellite Systems

The first satellite navigation systems ('TRANSIT'; 1960 onwards) used low-orbiting satellites. The orbit of the satellites was known to reasonable accuracy [in fact later 'NOVA' satellites used a small drag-matching plasma propulsion system] and is transmitted by the satellite.

When a satellite flew overhead, the surface vessel's position along the orbit depends on when it hears the signal. Its crossrange position is determined (ambiguously) by the Doppler shift - if the sub is far from the groundtrack, there will be a shallow doppler curve, while close to it the doppler curve is steep.

This allowed (surfaced) Polaris missile submarines to determine their position down to 150m or so, but satellite passes occur only once an hour or so. A significant error source is uncertainty in the drift of the submarine.

The Modern Era - The Global Positioning System (GPS)

The NAVSTAR GPS system, which we are using on our trip, began as joint USAF/Navy project in 1973. The first satellite was launched in 1978, and the system was declared fully operational in 1994 (on Feb 1 by the FAA; July 17 by the Air Force) - it had of course been widely used long before, notably during the Gulf War.

The system uses 24 satellites in orbits 11,000 nautical miles up (12 hour period). The satellites are in 6 orbital planes, each at 55° inclination. Signals from the satellites (which carry accurate rubidium clocks) are transmitted including the satellite's position and the time of transmission. With 3 satellites, a 2-D position can be determined. A more accurate (and/or 3-D fix) requires 4 satellites. With 24 satellites in the constellation, several are in view at any time.

Two signal streams are transmitted; the military (encrypted) 'P-code', and the 'C/A' code, available to all. The accuracy of the former is better than 20m. Depending on conditions (notably ionospheric disturbances, which alter the transit time of the signals) general accuracy is about 100m. Vertical accuracy is usually about 50% poorer.

Note that translating a 3-D position in a coordinate frame centered on the Earth's barycenter (as are the satellites) into a latitude, longitude and altitude is non-trivial, and depends on the reference shape used. For example, most GPS receivers use the World Geodetic System (WGS84), while most maps in the US use the North American Datum 1927 (NAD27). A WGS84 position plotted on a NAD27 chart in the Pacific Northwest would be 65ft S and 330ft W of its true position. These errors can be a mile or more in other parts of the world.

The effects of ionospheric disturbance can be compensated over modest distances by comparing in real-time the position measured at a fixed reference station with that from the movable one. This Differential GPS allows very accurate measurements to be made.

Militarily, accurate navigation is vital. Not only in itself, to dump shells, nukes or paratroops in the right place, or to navigate tanks on a featureless desert, but also because bad navigation is all too often a pretext e.g. the shooting down of KAL 007 over Siberia in 1983; the seizing of the USS Pueblo by North Korea in 1968 (claiming it was in territorial waters), or the Soviet submarine which ran aground next to a restricted Swedish naval base in 1981 claiming 'poor navigation'. The notion is highlighted in modern fiction (e.g. United Artists, 1997)

Incidentally, there are reports around of jammers, able to inhibit the operation of GPS receivers over radii of hundreds of km. There is a Russian system, GLONASS, which operates similarly to GPS, and combined GPS/GLONASS receivers are becoming available.

The Inverse Problem

Not always is it the user on the ground that wants to determine his/her position. A constellation of satellites (now retired) called Vela used the differential arrival times of neutrons to determine their source, and hence determine where nuclear explosions had occurred.

The Iridium satellite constellation (built in Phoenix) uses (electronically) steerable beams on its antennae to provide cellular phone service. The beam footprint is only 10km or so wide; it follows that the satellite has to know where the phone is.....

Similarly, not all satellite tracking uses NORAD. By measuring the time of acquisition and loss of signal, and the doppler profile, of a satellite, a single, simple groundstation can constrain a satellite orbit.

Swords into Ploughshares, and the Planetary Connection

The improved safety of marine and aviation transport benefits us all. Accurate satellite tracking allows neat things like interferometric radar imaging, to observe ice flows, the swelling of magma chambers under volcanos. These effects can also be observed by accurate DGPS.

Satellite tracking also allows the determination of the gravity field - and hence such wonders as the core of Io, masscons on the Moon, etc. A system like the drag compensation system used on NOVA will be used on Gravity Probe B.

Because GPS signals are affected slightly by ionospheric disturbances and water vapor in the atmosphere, there are plans to use the large GPS constellation to perform tomography of these properties - essentially there are dozens of radio-occultations going on all the time.

Satellite Navigation by Eye

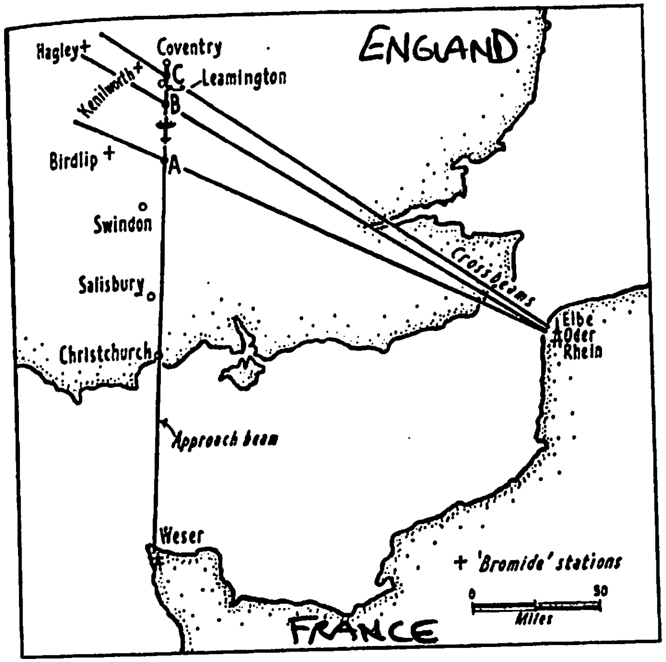
•f you are at high latitudes, you will see many (polar orbiting) satellites moving N-S on a clear night: the inclination distribution of satellites seen at lower latitudes is much broader.
•In Europe, look at peoples satellite TV dishes : note (1) they are smaller (European Direct Broadcast satellites use higher transmit power) and (2) they point very low on the horizon.

References

'Longitude: The true story of a lone genius who solved the greatest scientific problem of his time', Dava Sobel, 1995 (*Harrington's Tale*) QB 225. S64
'Instruments of Darkness', Alfred Prince (*The remarkable tale of electronic innovation and countermeasure during WWII*) UG612.P74 1978
'The Longitude discovered by the eclipses, occultations and conjunctions of Jupiter's Planets' William Whiston, QB 225. W464 (Special Collection) 1738
'Men of Invention and Industry' Samuel Smiles 1884. (*biography, incl. Harrington*) 609 S641
Tomorrow Never Dies, United Artists, 1997 (Not the best Bond Film, but not bad)
Marine Electronic Navigation S. F. Appleyard. (*Good intro to LORAN, TRANSIT, GPS*) VK 560. A66 1980

Web/usenet

sci.geo.satellite-nav newsgroup
http://galaxy.einet.net/editors/john-beadles/introgps.htm



THE LAYOUT OF THE X-BEAMS OVER COVENTRY ON THE NIGHT OF 14th NOVEMBER 1940

Point A—the first cross beam (*Rhein*): the aircraft closes on to the approach beam (*Weser*). The distance from A to B is 30 kilometres.
Point B—the second cross beam (*Oder*): aircraft observer presses button to start the bombing clock. The distance from B to C is 15 kilometres.
Point C—the third cross beam (*Elbe*): aircraft observer presses button to stop first hand of bombing clock; second hand moves round towards the first. The distance from C to Coventry is 5 kilometres.
Target Coventry: hands on bombing clock overlap, closing pair of electrical contacts to release bombs automatically.

EARLY RADIO NAVIGATION

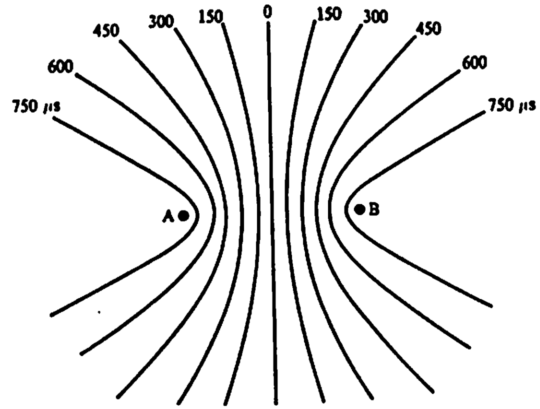


Figure 6.2 A set of hyperbolae for specific time differences.

LORAN, DECCA

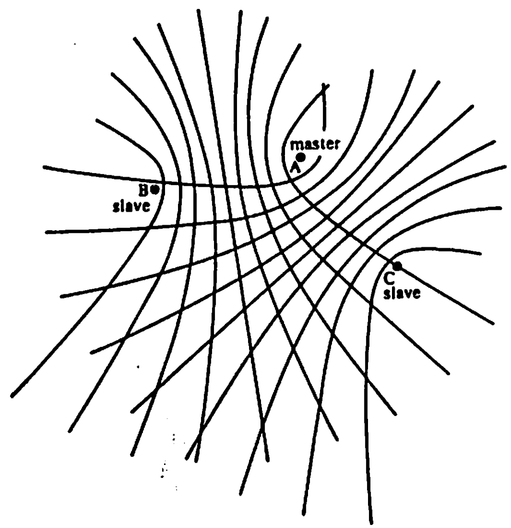


Figure 6.3 Two hyperbolic patterns can be obtained from three transmitters.

RECEIVER MEASURES Δt_{AB}, Δt_{AC}
→ where curves cross indicates position

 (TRANSIT)

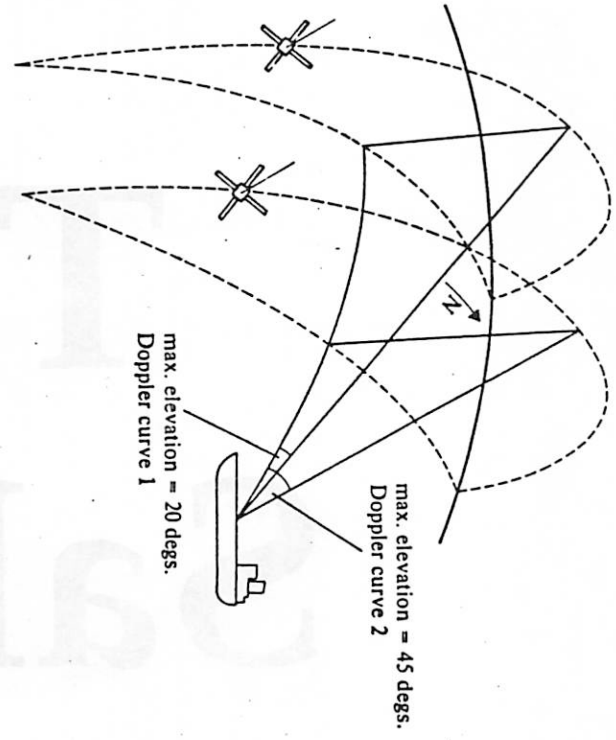


Figure 11.8 **The shape of the Doppler curve relates to elevation and hence vessel's longitude. The point of zero Doppler shift relates to latitude.**

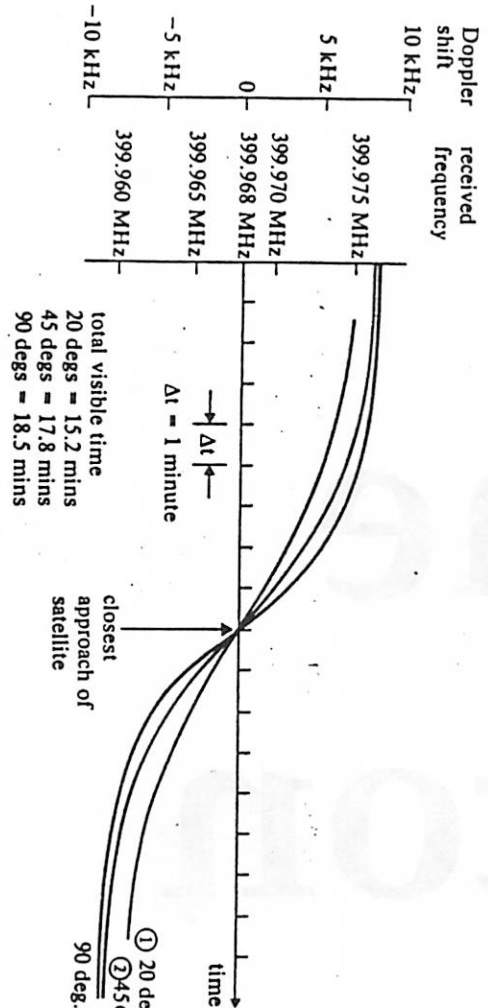


Figure 11.7 **The Doppler shift curves resulting from observing satellite passes.**

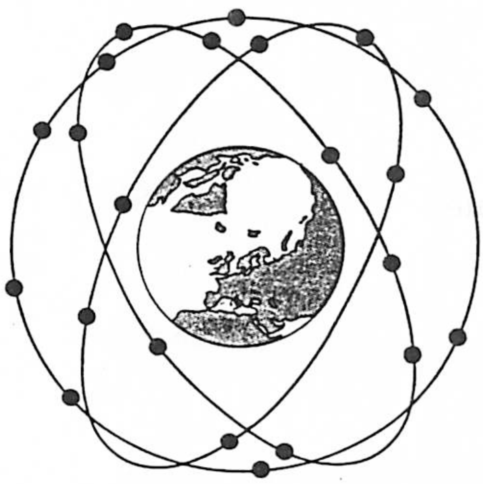


Figure 12.1 *The twenty-four Navstar satellites will be in three orbital planes.*

GPS

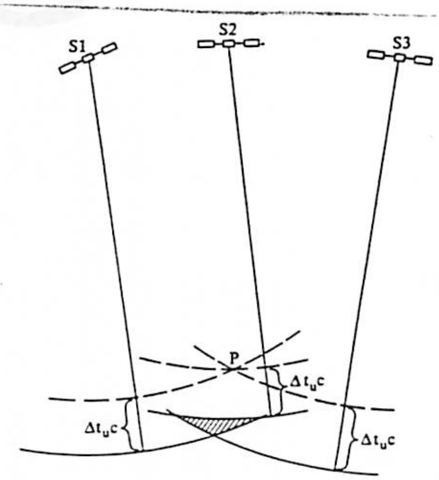
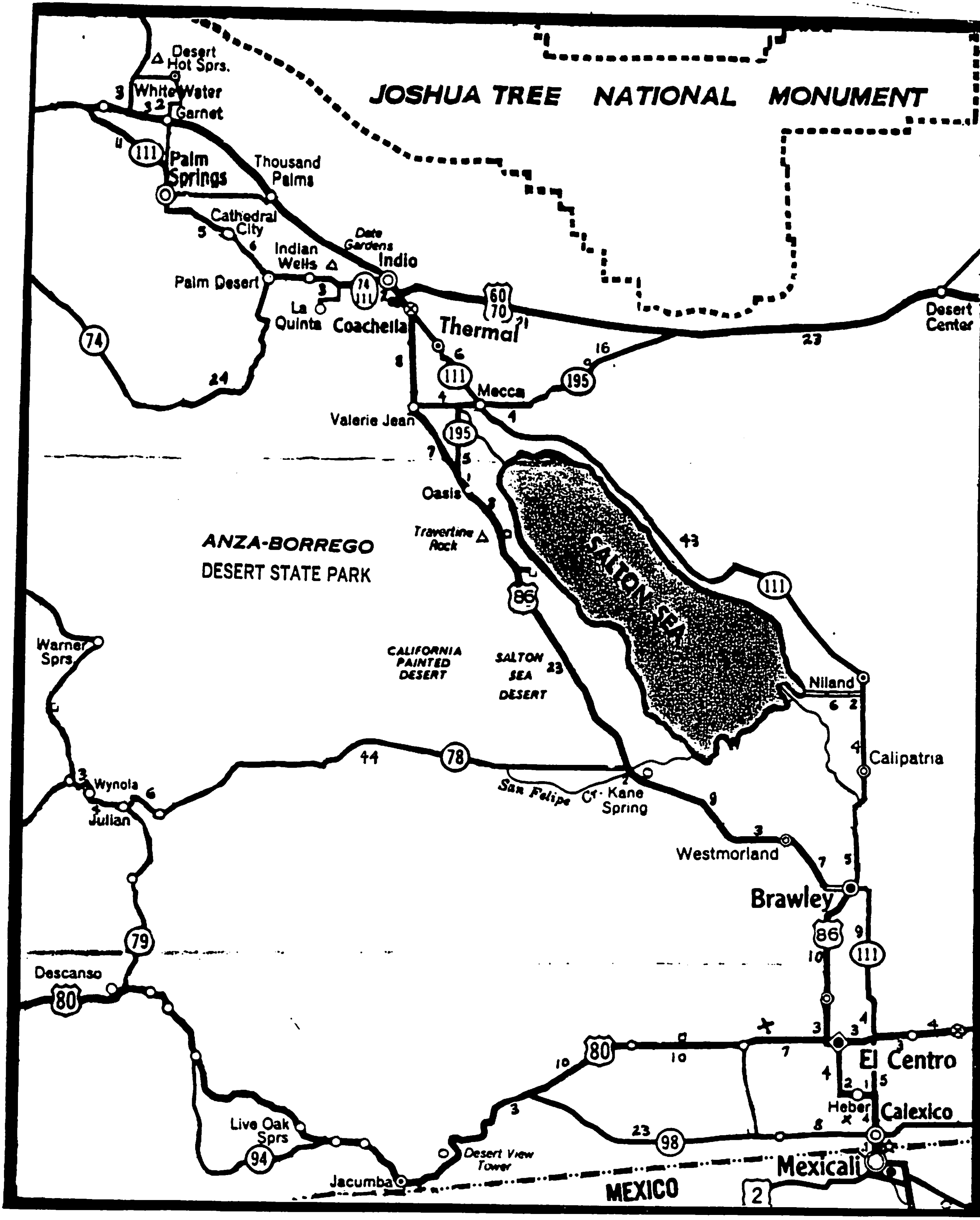


Figure 12.3 *The measured ranges (pseudo-ranges) will not meet at a point until corrected for the effect of receiver clock error* (Δt_u .C). (using a 4th satellite)

The Salton Sea

Joe Spitale


JOSHUA TREE NATIONAL MONUMENT
Desert Hot Sprs.
White Water
Garnet
Palm Springs
Thousand Palms
Cathedral City
Indian Wells
Date Gardens
Indio
Palm Desert
La Quinta
Coachella
Thermal
Desert Center
Mecca
Valerie Jean
Oasis
Travertine Rock
ANZA-BORREGO
DESERT STATE PARK
SALTON SEA
CALIFORNIA PAINTED DESERT
SALTON SEA DESERT
Warner Sprs
Niland
Calipatria
Wynola
Julian
San Felipe Cr.
Kane Spring
Westmorland
Brawley
Descanso
El Centro
Heber
Calexico
Live Oak Sprs
Desert View Tower
Jacumba
MEXICO
Mexicali

- **Geologic History and Setting of the Salton Trough**

    - Pullapart zone, growing due to dextral motion along two parallel traces of the San Andreas Fault.

    - Crustal attenuation, volcanism, normal faulting[4].

    - Mostly filled with sediment[3]
        - Shallow marine
        - Colorado river

- **Record of Paleolakes in the Salton Trough[1]**

    - Evidence of previous seas
        - Fossil oyster beds
        - Ancient shorelines

    - Gulf of California may have once extended north towards San Bernadino mountains

    - Northern portion of trough cut off by Colorado River delta -> periodic lakes due to flooding of Colorado river

    - Most recent lake : Lake Cahuilla
        - Existed as recently as 300 years ago according to legends of local tribes.
        - Diversion of Colorado River ultimately caused desiccation.
        - Lake Cahuilla disappeared slowly -> Salton Sink.

- **History of the Salton Sea[1],[2]**

    - 1901: Water diverted from Colorado River for irrigation in Imperial Valley -> Salton Sea began to form from runoff.

    - 1904: ~0.2 feet deep.

- 1905: Colorado River flood, took two years for irrigators to regain control.

- 1907: Maximum water volume, ~80 ft deep, 45 miles long, ~520 square miles.

- Generally disappearing since 1907.

- Water sources: rain on surface, runoff from irrigation, groundwater flow.

- Water sinks: evaporation.

- High salinity due to accumulated salts on bed as well as concentration due to evaporation.

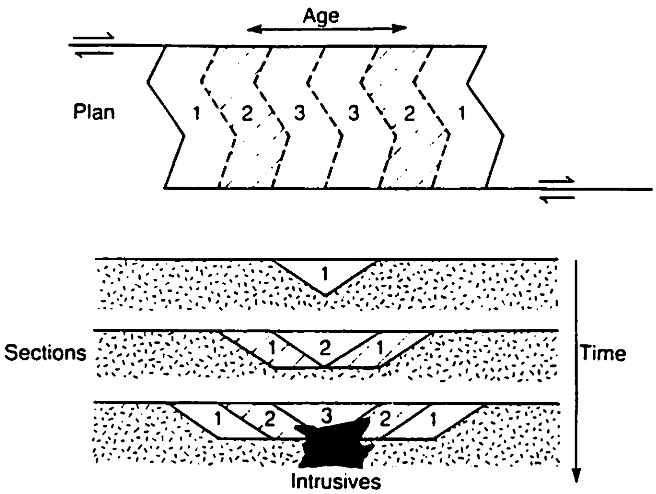


Fig. 7.10 Stages in the formation of a pul apart basin.

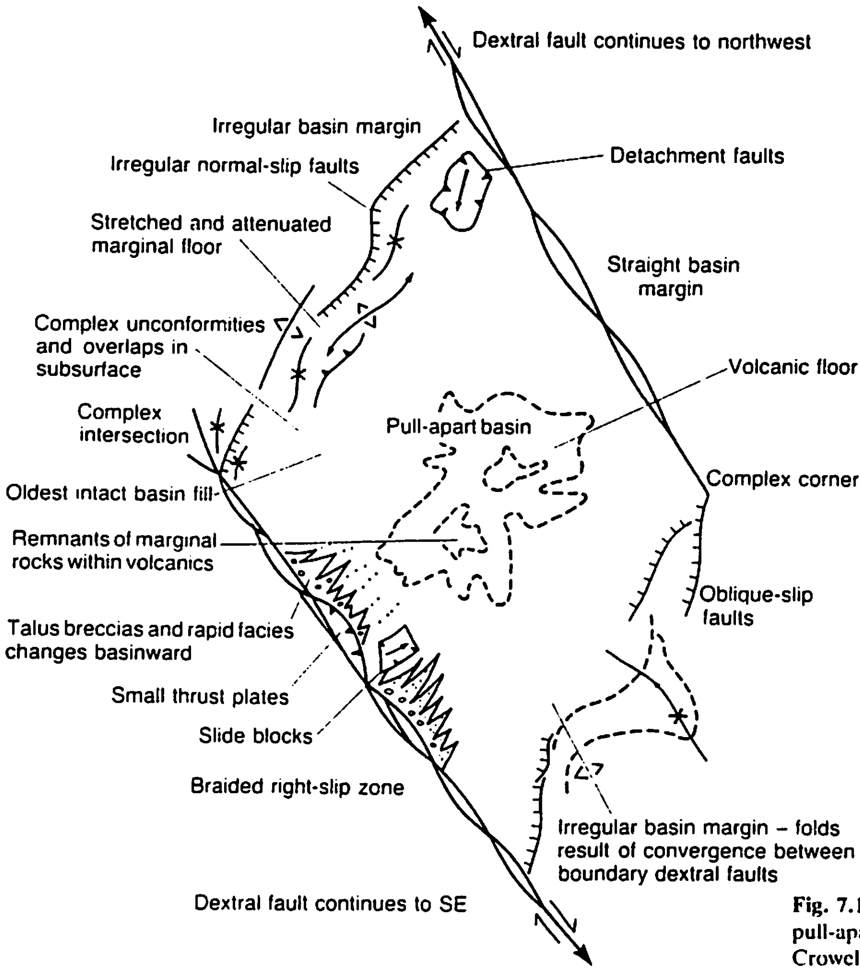


Fig. 7.11 Sketch map of an idcali: pull-apart basin (redrawn from Crowell, 1974b, with permission fr the Society of Economic Palaeontologists & Mineralogists)

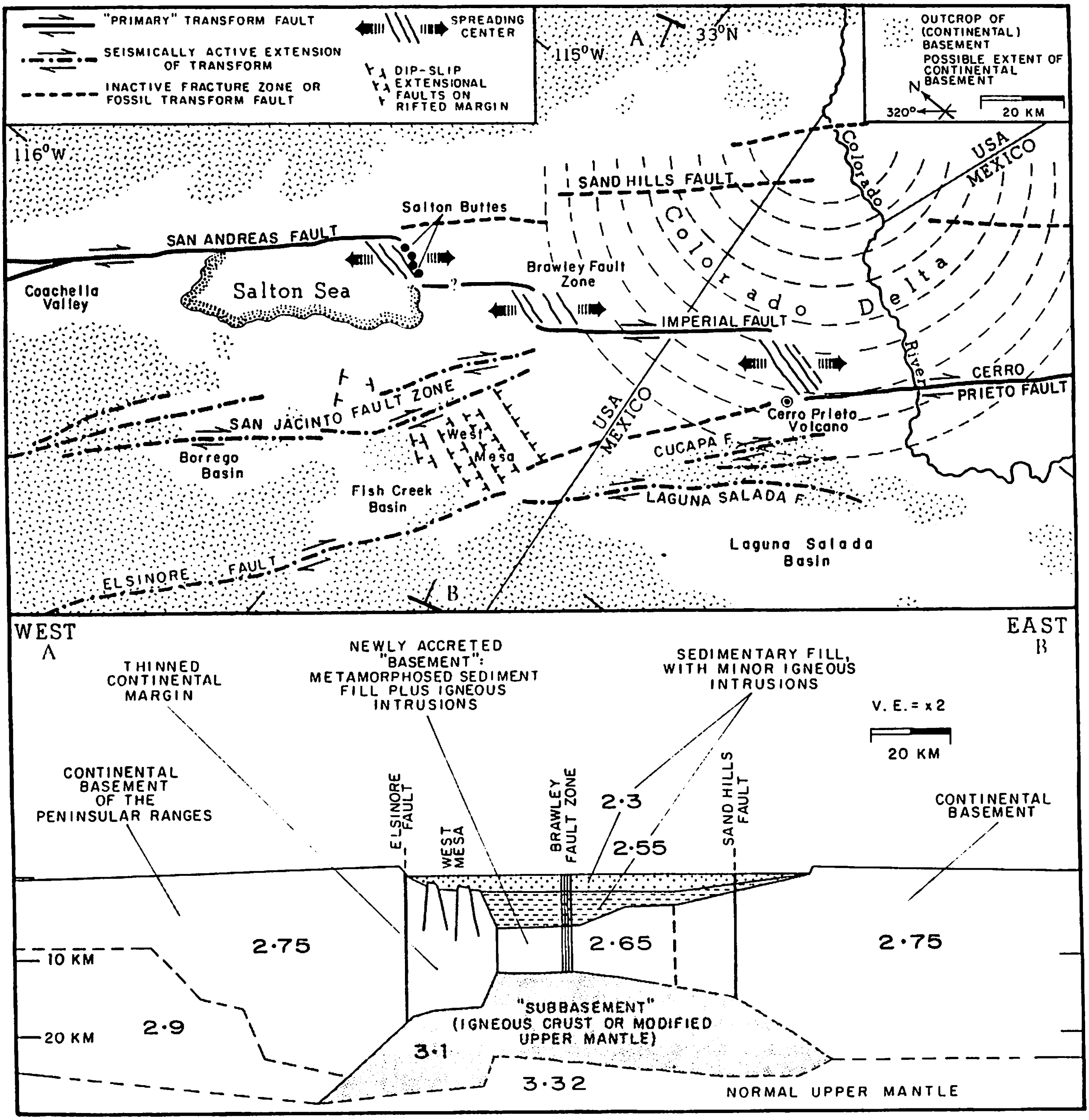


Figure 6. Sketch map and crustal section of Salton Trough (after Fuis and others, 1982). Dashed boundaries in the section are controlled by gravity modeling only (not by refraction). Numbers are estimated densities (g/cm^3).

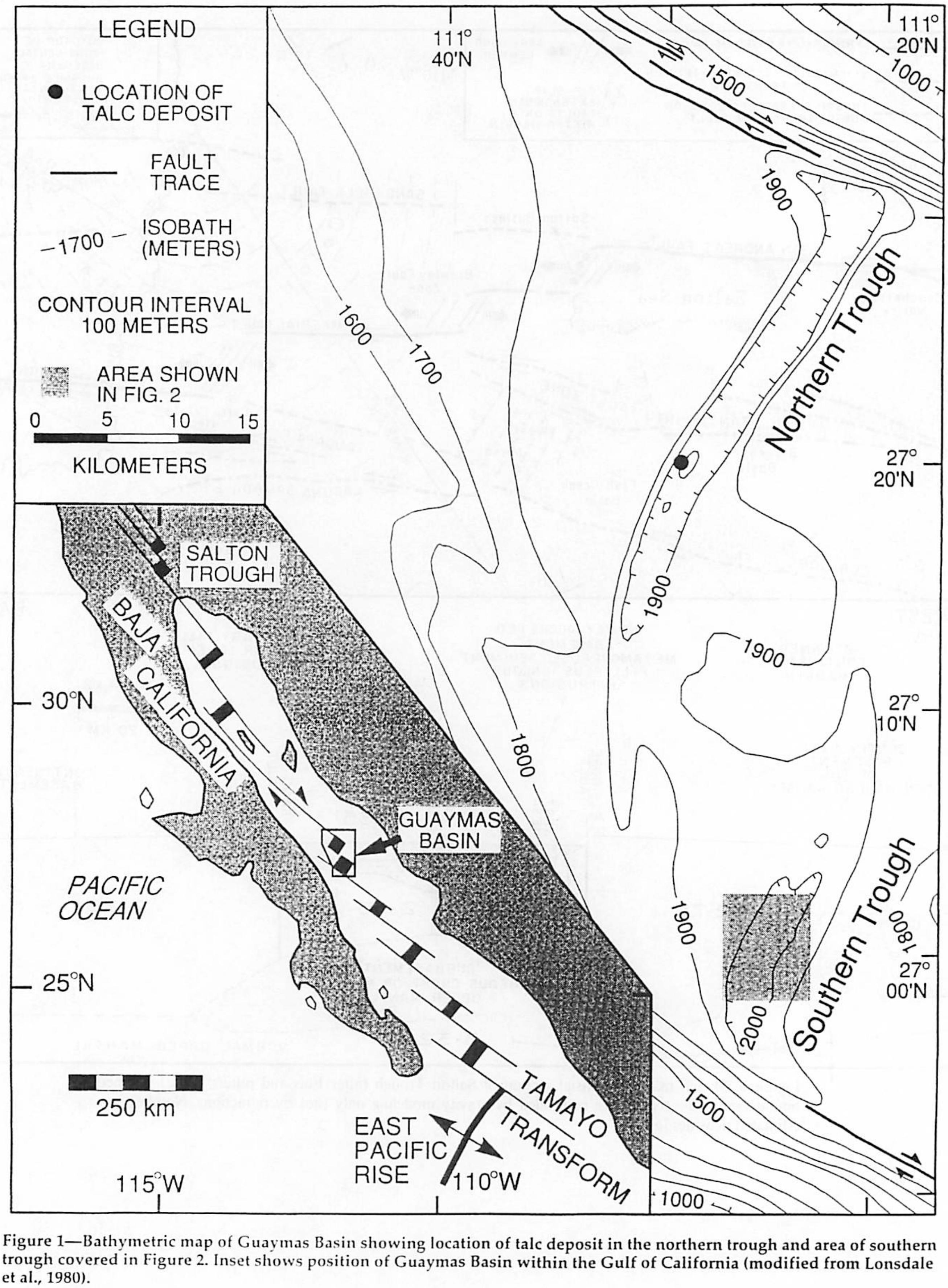


Figure 1—Bathymetric map of Guaymas Basin showing location of talc deposit in the northern trough and area of southern trough covered in Figure 2. Inset shows position of Guaymas Basin within the Gulf of California (modified from Lonsdale et al., 1980).

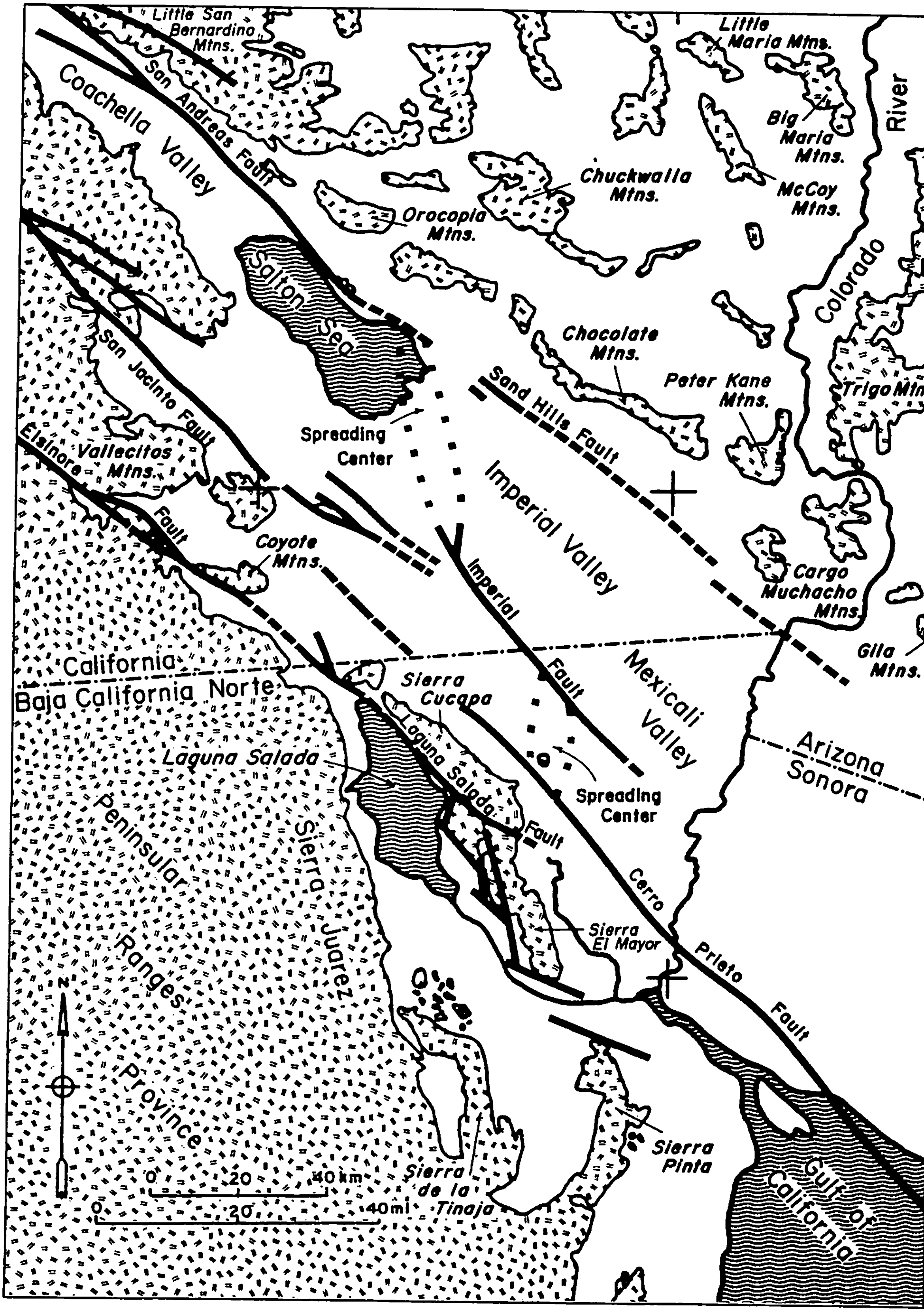


Figure 1—Map showing major structural and physiographic elements of the Salton trough. Note location of the Laguna Salada basin and the Sierra Cucapa along its southwestern margin.

References

1. D.T.MacDougal; *The Salton Sea* Carnegie Institute of Washington, 1914
2. W.M.Littlefield; *Hydrology and Physiography of the Salton Sea, CA* USGS, 1966
3. P. Lonsdale; *Geology and Tectonic History of the Gulf of California* from *The Eastern Pacific Ocean and Hawaii* The Geological Society of America, 1989
4. K.J. Mueller, T.K.Rockwell; *Late Quaternary Structural Evolution of the Western Margin of the Sierra Cucapa, Northern Baja California* from *The Gulf and Peninsular Province of the Californias* The American Association of Petroleum Geologists, 1991

TECTONIC EVOLUTION IN THE VICINITY OF ANZA BORREGO

Windy Jaeger

REFERENCES

Dibblee, T. W., Jr. (1984) Stratigraphy and tectonics of the San Felipe Hills, Borrego Badlands, Superstition Hills, and vicinity: in Rigsby, C., ed., *The Imperial Basin - tectonics, sedimentation and thermal aspects,* Pacific Section Society of Economic Paleontologists and Mineralogists, Bakersfield, California, 31-44.

Fuis, G. S. and Kohler, W. M. (1984) Crustal structure and tectonics of the Imperial Valley region, California: in Rigsby, C., ed., *The Imperial Basin - tectonics, sedimentation and thermal aspects,* Pacific Section Society of Economic Paleontologists and Mineralogists, Bakersfield, California, 1-13.

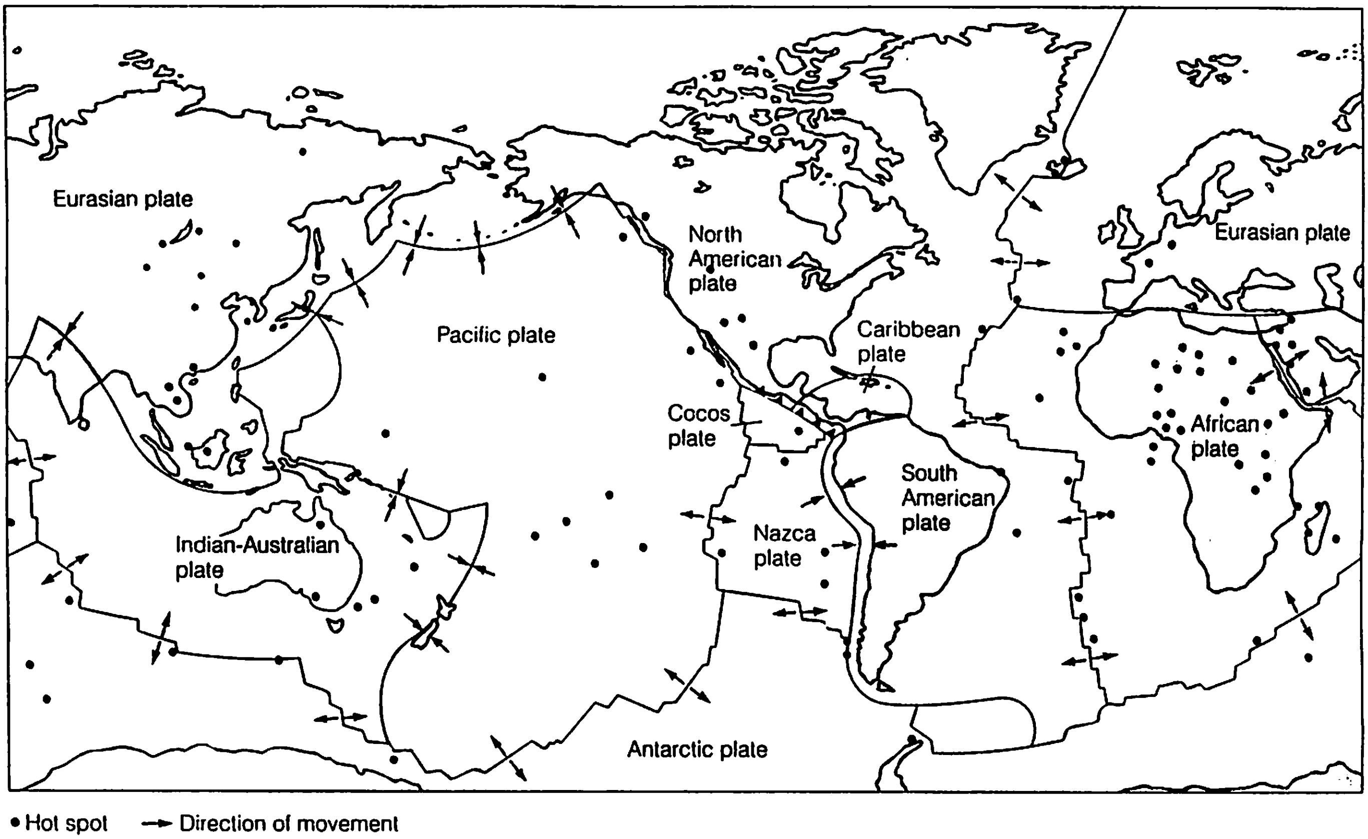
Gibson, L. M., Malinconico, L. L., Downs, T., and Johnson, N. M. (1984) Structural implications of gravity data from the Vallecito-Fish Creek Basin, Western Imperial Valley, California: in Rigsby, C., ed., *The Imperial Basin - tectonics, sedimentation and thermal aspects,* Pacific Section Society of Economic Paleontologists and Mineralogists, Bakersfield, California, 15-29.

Kearey, P. and Vine, F. *Global Tectonics*, Blackwell Scientific Publications, Oxford.

Monroe, J. S. and Wicander, R. *Physical Geology*, West Publishing Company, St. Paul Minnesota.

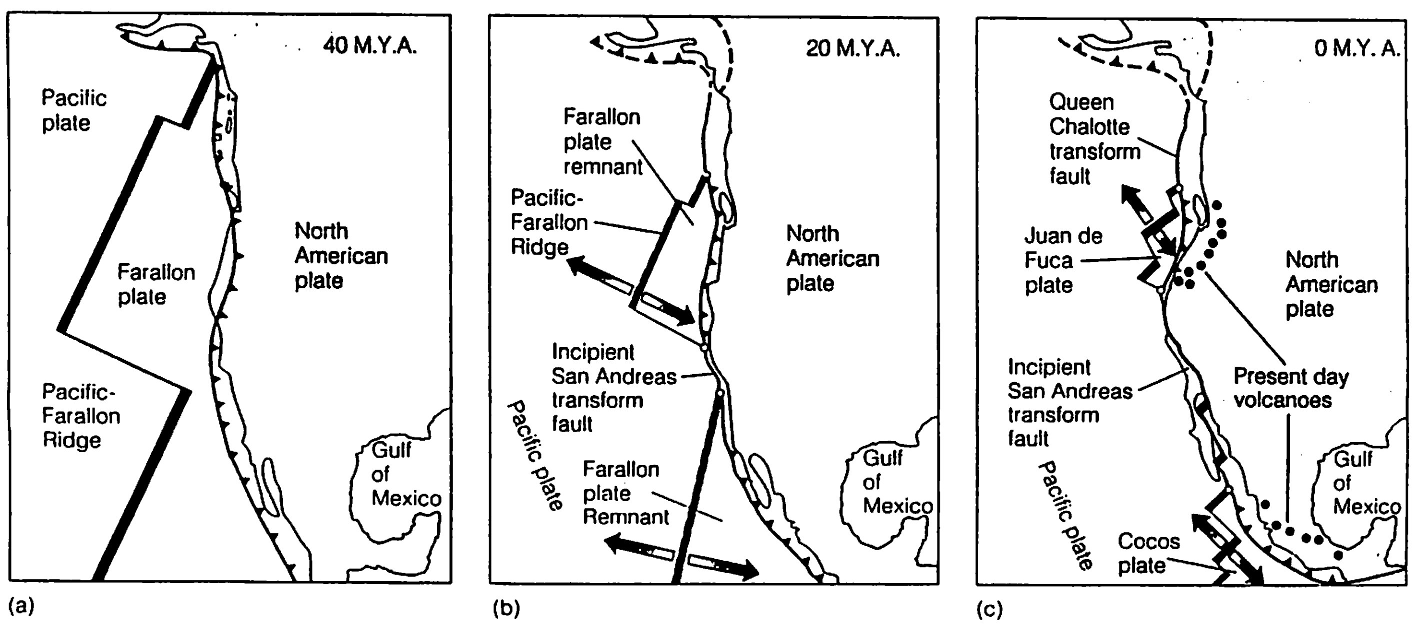
Prothero, D. R. *Interpreting the Stratigraphic Record,* W. H. Freeman and Company, New York.

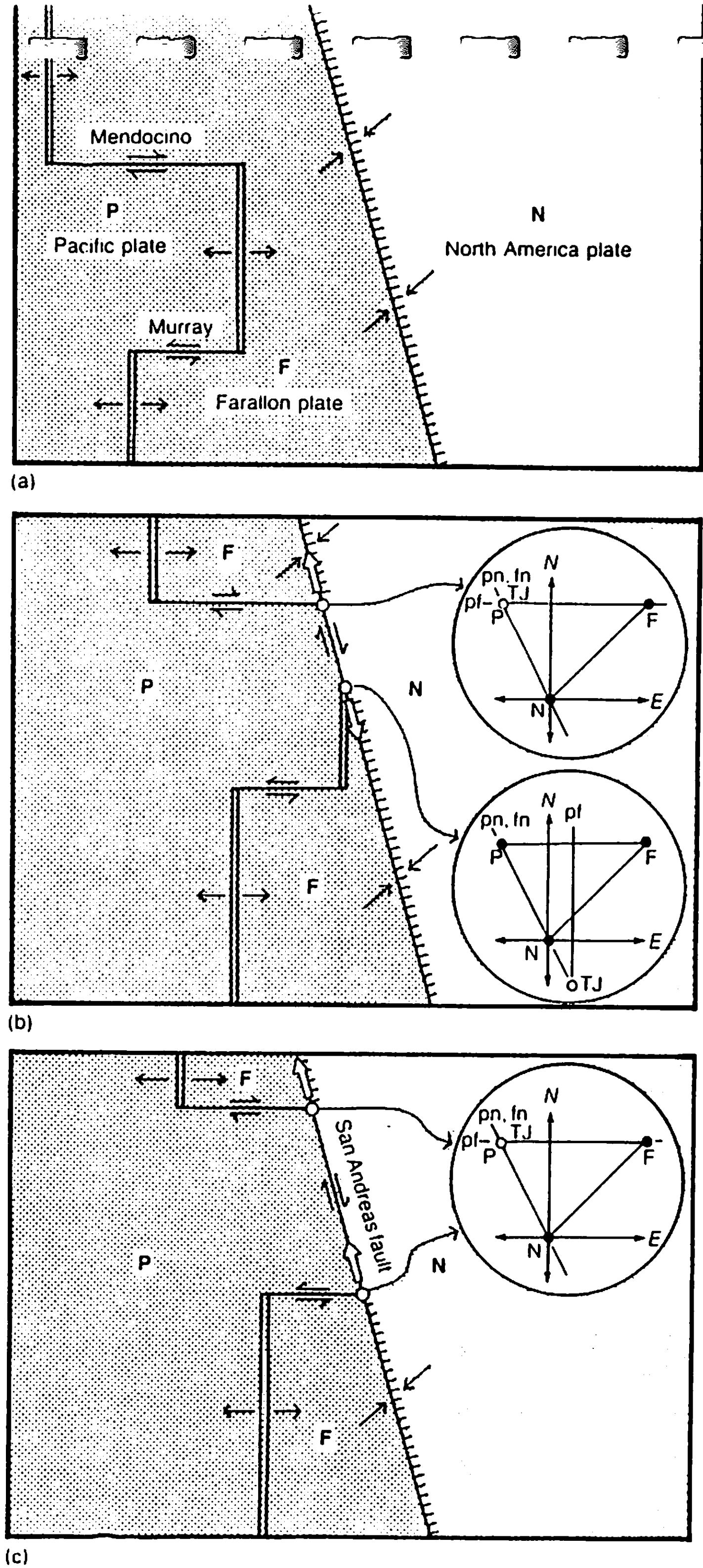
Sylvester, A. G. (1991) Geologic structure, transpression, and neotectonics of the San Andreas Fault in the Salton Trough, California: in Walawender, M. J. and Hanan, B. B., eds., *Geologic Excursions in Southern California,* Geological Society of America, San Diego, California, 378-387.



▶ FIGURE 12-14 A map of the world showing the plates, their boundaries, direction of movement, and hot spots.

▶ FIGURE 13-40 (*a*), (*b*), and (*c*) Three stages in the westward drift of North America and its collision with the Pacific-Farallon ridge. As the North American plate overrode the ridge, its margin became bounded by transform faults rather than a subduction zone.





'ig. 7.25 Evolution of the San \ndreas Fault (redrawn from Cox & lart, 1986).

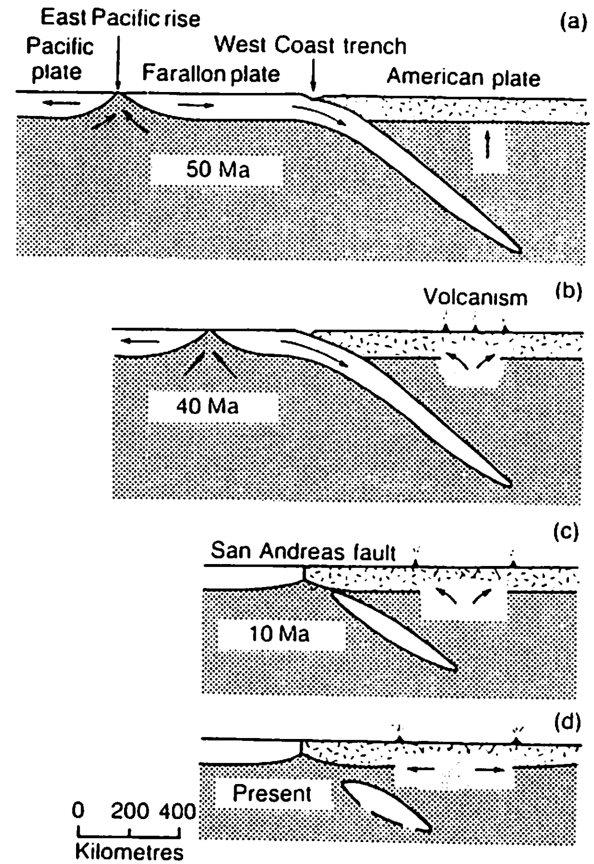


Fig. 8.36 Inferred Cenozoic evolution of the Basin and Range Province (redrawn from Scholz *et al.*, 1971, with permission from the Geological Society of America).

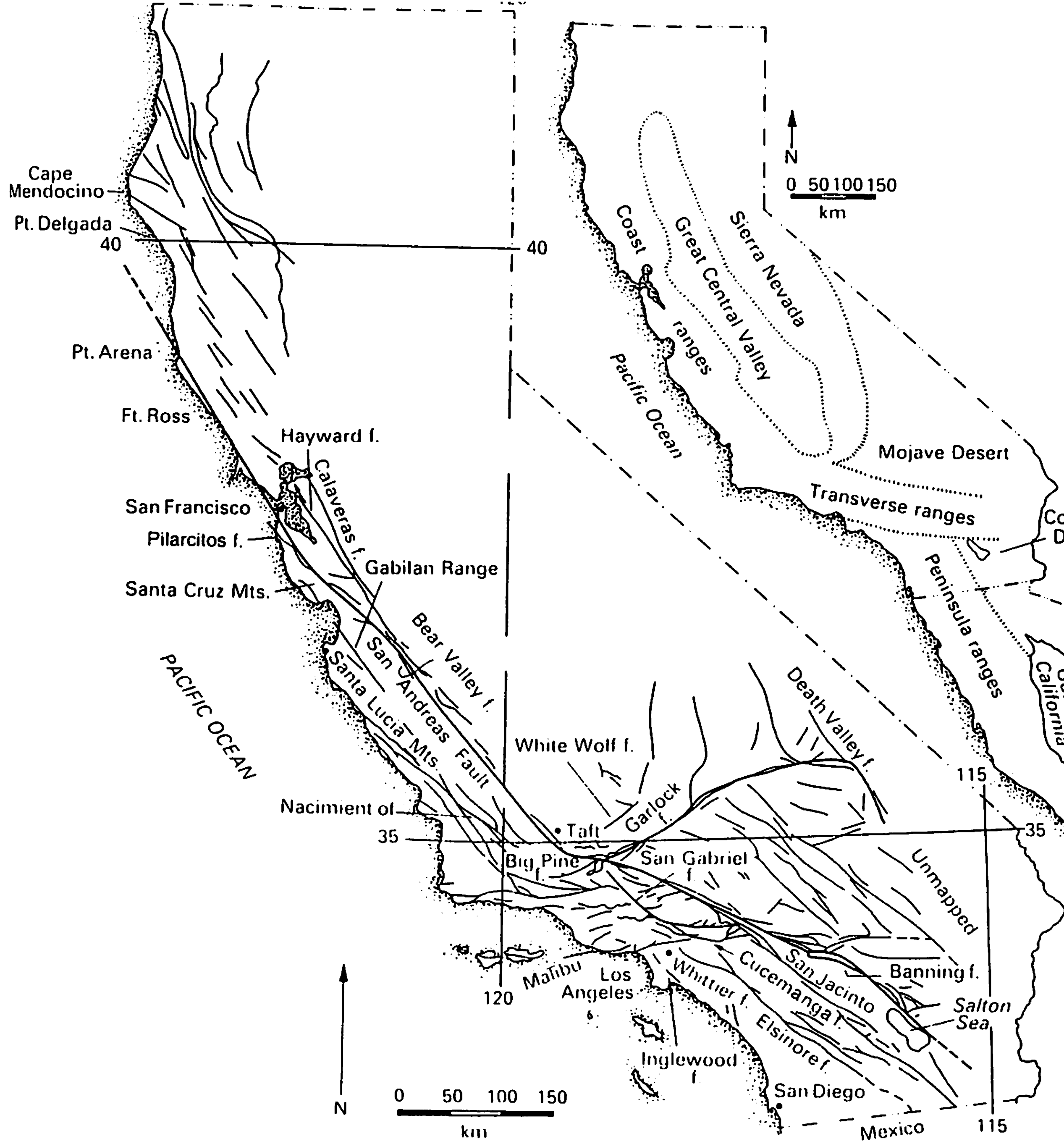


Fig. 7.8 Generalized fault map of coastal and southern California (redrawn from Crowell, 1962, with permission from the Geological Society of America).

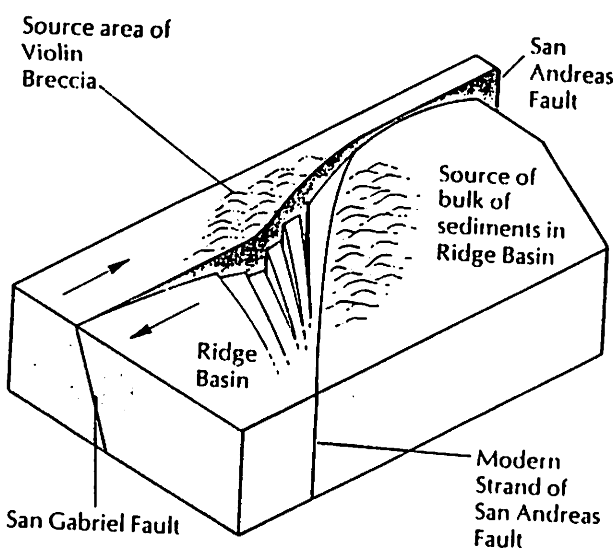


Figure 9.17 Block diagram showing the origin of the Ridge Basin as a sigmoidal bend in the San Andreas Fault. This explains the extremely steep yet narrow geometry of the basin. From Crowell and Link (1982).

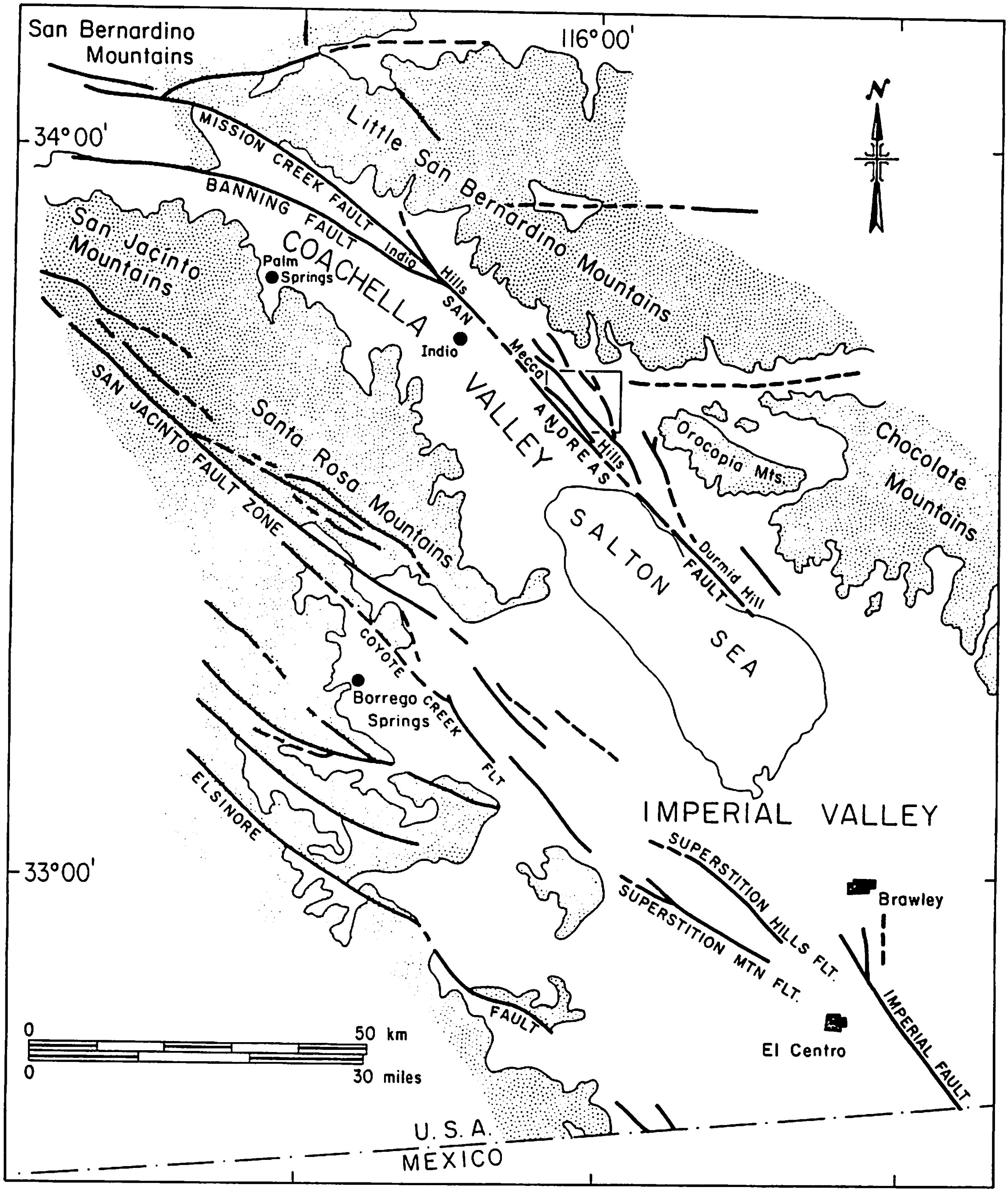


Fig. 1. Map of the principal faults, mountainous areas underlain by pre-Cenozoic crystalline rocks (stippled), Tertiary and Quaternary sedimentary rocks (no pattern), and main towns in the Salton Trough. The polygon across the San Andreas fault zone north of the Salton Sea outlines the map area in the central Mecca Hills in Figure 4. From Sylvester and Smith [1976], reprinted with permission of the American Association of Petroleum Geologists.

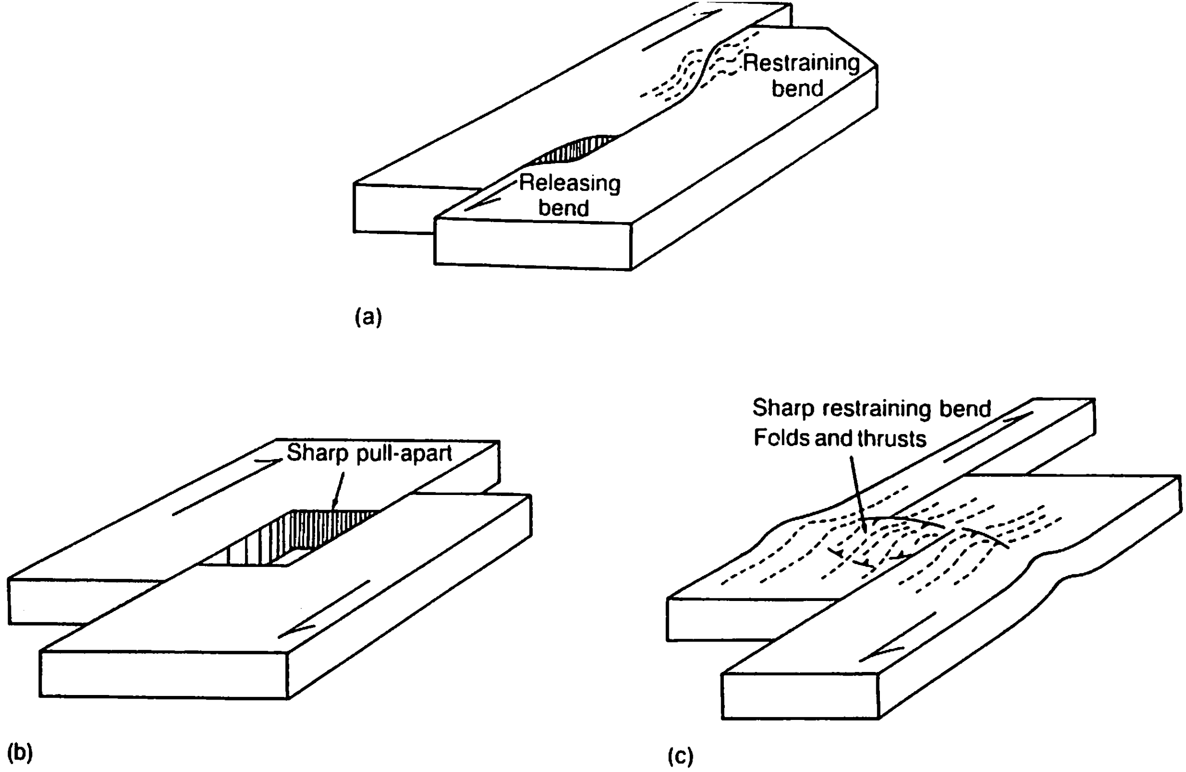


Fig. 7.9 Structures developed along continental wrench faults: (a) at a double bend a pull-apart forms at a releasing bend and deformation and uplift at a restraining bend; (b) sharp pull-apart; (c) severe deformation at a sharp restraining bend causing folding and thrusting (redrawn from Crowell, 1974b, with permission from the Society of Economic Palaeontologists & Mineralogists).

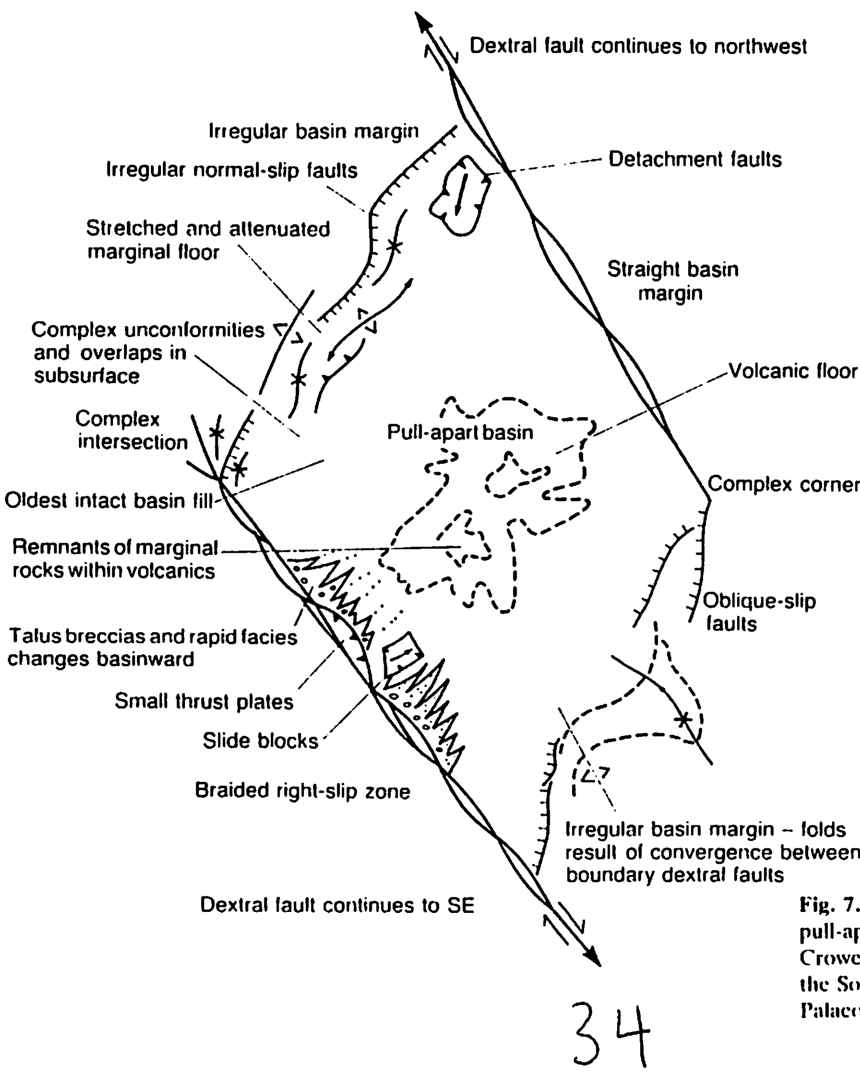


Fig. 7.11 Sketch map of an idealized pull-apart basin (redrawn from Crowell, 1974b, with permission from the Society of Economic Palaeontologists & Mineralogists).

Plate Tectonic Origins of Baja California and the Baja-British Columbia Connection

Josh Emery and Cynthia Phillips

For such a small piece of continental crust, the Baja Peninsula has had a rather long and eventful history. Attempts to understand this history necessarily take us back in time over 100 million years and involve a tremendous cast of tectonic characters stretching from the equator to Alaska, some still with us, others long since erased from the face of the Earth. Our story begins with a very typical, ordinary subduction zone, but quickly begins to weave through the vast array of tectonic expressions on the pacific coast, from the majestic Rocky Mountains to the deadly San Andreas fault system. Below is a timing of major events pertinent to this story and a few illustrative figures to help navigate through the complicated history of Baja California.

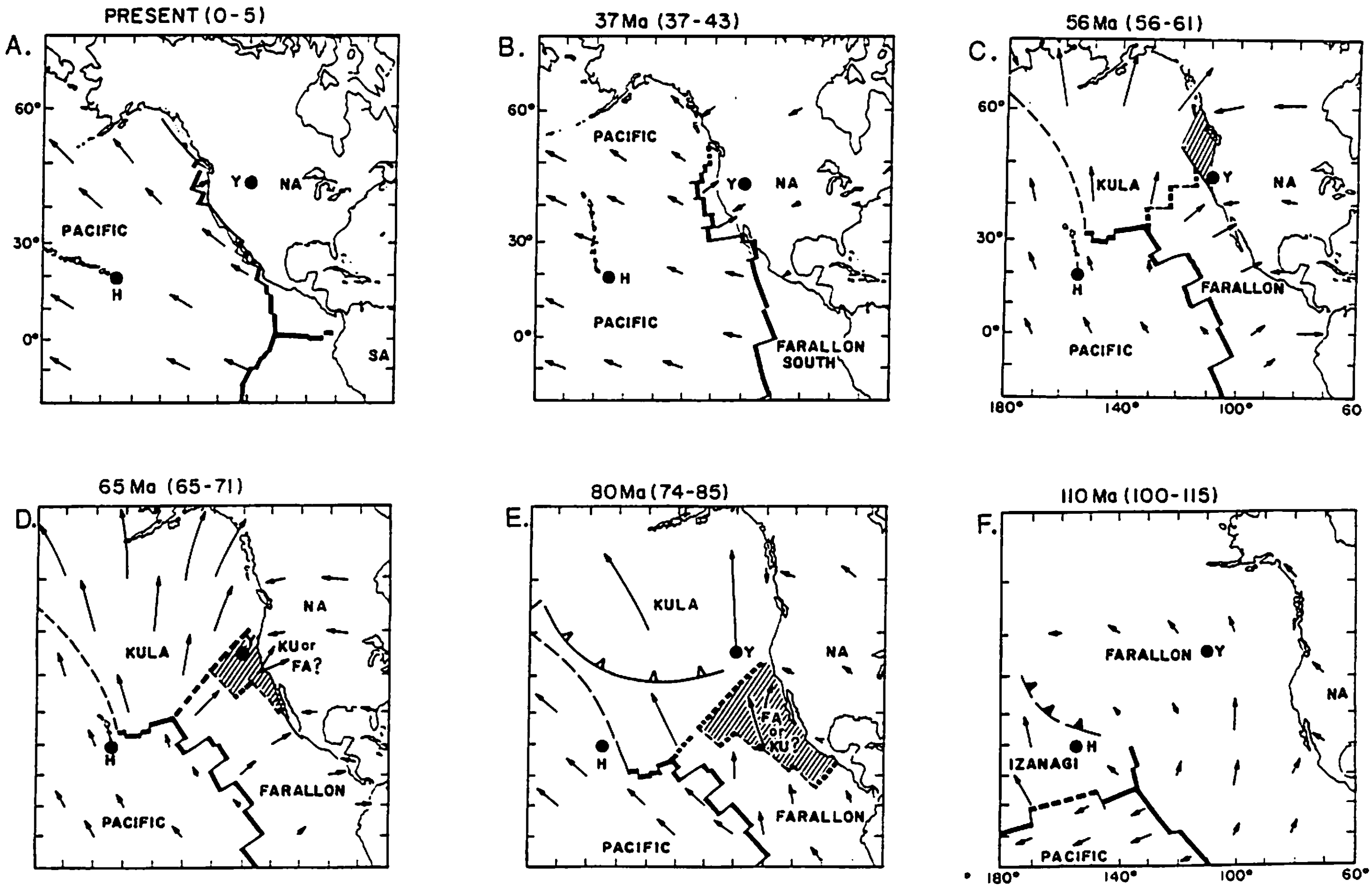


Figure 1. Late Mesozoic and Cenozoic paleogeographic maps and plate motions constructed with respect to the hot spots, after Engebretson and others (1985). Shaded areas in C, D, and E indicate range of possible locations for the Kula-Farallon spreading center. Y = Yellowstone hot spot, H = Hawaiian hot spot.

~120 Ma Pacific Ocean dominated by Farallon plate which is subducting beneath North America(NA).

Pacific plate isolated west of ~180° long. in between Izanagi plate to north and Phoenix plate to south.

All plate boundaries are ridges (except NA).

Fig. 1

~90 Ma Formation of Kula plate (fractures off north Farallon).

Kula has very fast northward motions (up to 17 cm/yr).

At roughly this time the Santa Lucia allochthon (southern CA) and the Peninsular Ranges terrain (Baja CA) are amalgamating near the equator and Central America/southern Mexico, respectively.

Figs. 1 and 2

~90-50Ma Santa Lucia emplaced on NA at southern CA.

Peninsular Ranges emplaced at northern Mexico.

Fig. 2

~30 Ma Farallon-Pacific spreading ridge begins subducting under NA at southern CA or northern Baja.

Farallon plate now fractured into smaller plates
- continue transport and rotation of microplates until present.

Triple junction travels north and south along coast as ridge subducts, changing boundary from subduction to shear.

Fig. 1

~12 Ma Triple junction south of Baja.

Faults taking up shear begin transferring inland.

Fig. 3

~6-3.5 Ma Pull apart basins forming --> Proto-gulf.

Tosco-Abreojos fault still active (west of Baja).

Baja essentially a microplate.

~3.5 Ma to present

Baja becomes part of Pacific plate (TA fault inactive).

Oceanic spreading began in gulf ~2.6 Ma

Fig. 3

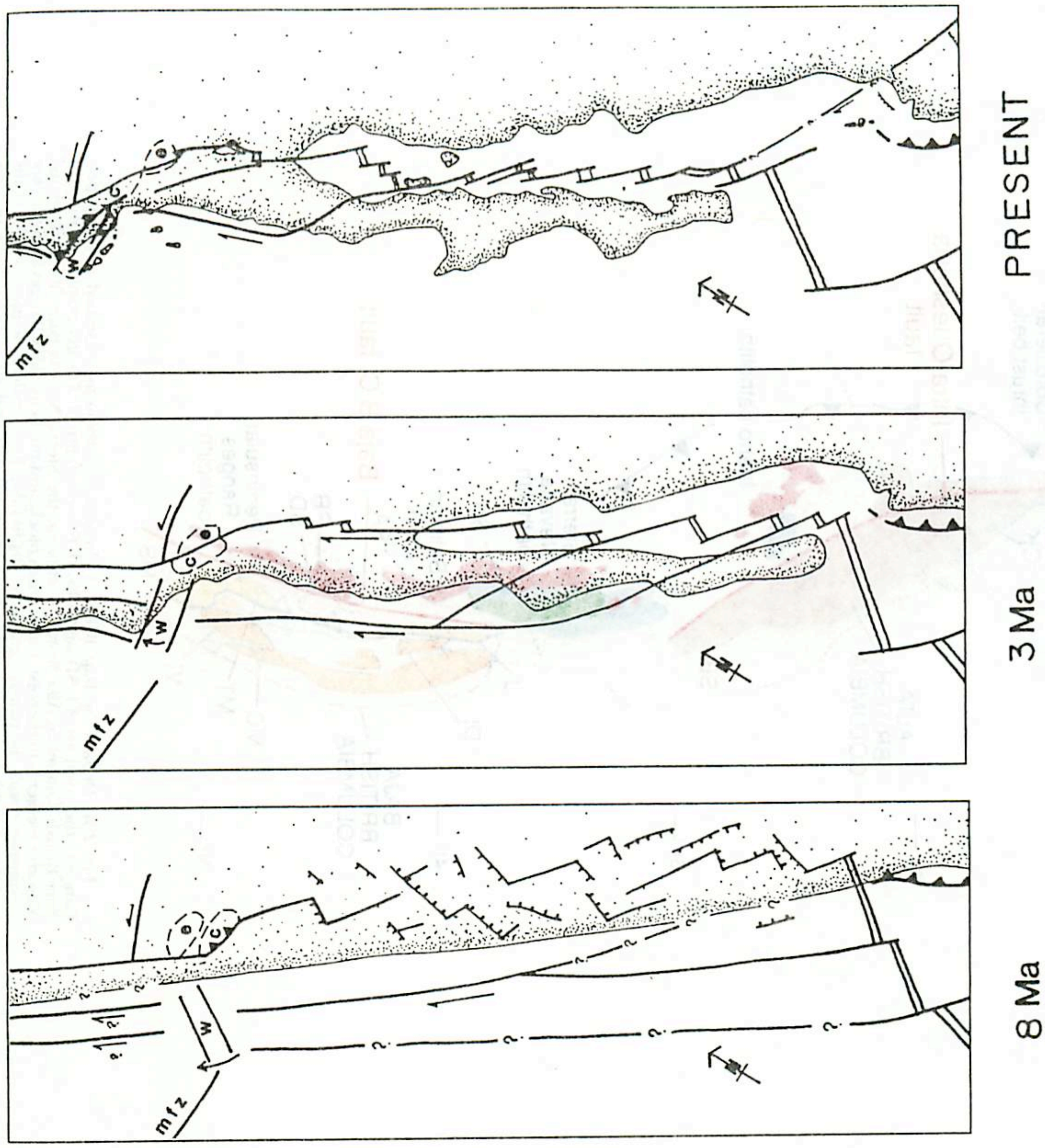


Figure 2—Schematic tectonic development of the Gulf of California region. These figures show major faults thought to be active at each indicated time.

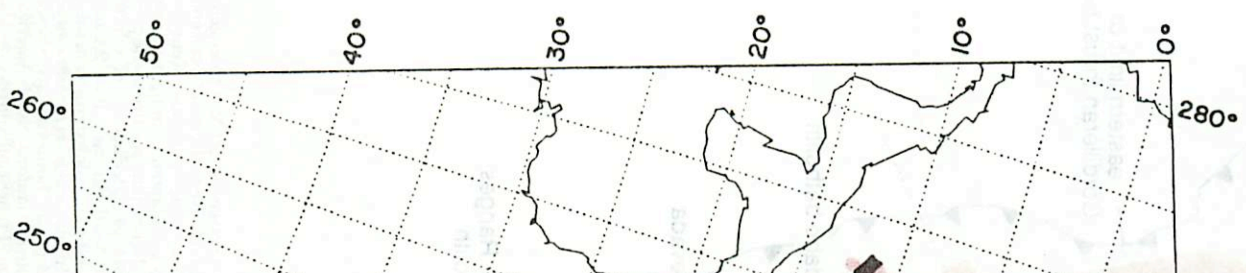


Figure 3 —Present-day and expected Cretaceous locations of the Peninsular Ranges terrane and Santa Lucia allochthon relative to North America.

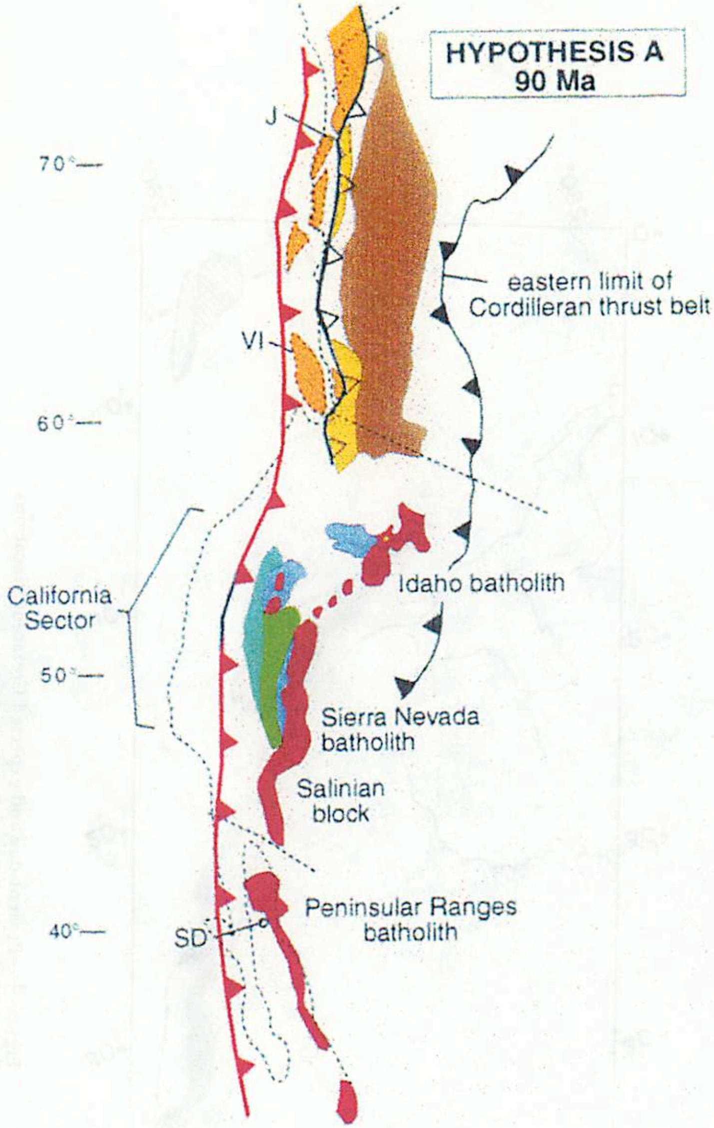


Fig. 2. Alternative hypotheses for early Late Cretaceous (90 Ma) paleogeography of the western margin of North America. Latitudes are relative to the mid-Cretaceous (124-88 Ma) reference pole for cratonic North America from Van Fossen and Kent (1992). The present-day coastline and international boundaries are adapted from figure 1 and depicted with a dashed line. The location and orientation of the coastline relative to the paleolatitudinal grid are determined by the paleolatitude and paleodeclination of selected coastal localities assuming that they were fixed to cratonal North America. Both 2A and B of this figure incorporate the removal of 275 km of east-west Cenozoic extension in the California sector east of the Sierra Nevada batholith. (A) The Insular and Intermontane superterranes and the Coast Mountains orogen along their common boundary are shown in their expected (that is, present) latitudinal positions relative to cratonic North America at 90 Ma. The red barbed line represents a single, west-facing, "Franciscan" convergent plate boundary extending the length of the continental margin. The position of the Peninsular Ranges batholith results from removing about 300 km of dextral slip on the San Andreas fault (fig. 1). The position of the Salinian block is determined by removing about 500 km of dextral slip on the San Andreas and earlier faults. Both these restorations are consistent with commonly cited geologic evidence (Dickinson, 1983; Butler, Dickinson, and Gehrels, 1991).

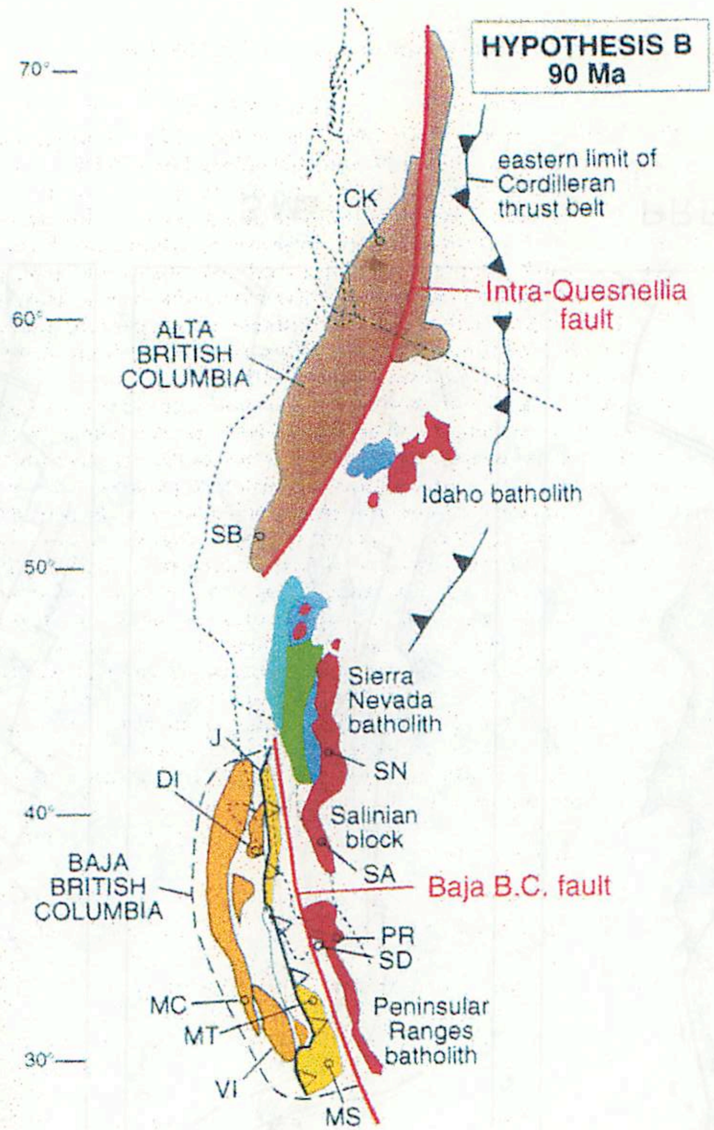


Fig. 2(B) Depicts the Baja British Columbia hypothesis as presented in this paper. Compare the positions of J, SD, and VI with those in figure 1. The geographic positions of Baja British Columbia, Alta British Columbia, the Sierra Nevada batholith and related Mesozoic elements to the west, the Salinian block, and the Peninsular Ranges batholith are all consistent with the paleomagnetic results in table 1 and reflect the mean values of the northward displacements calculated from corrected observed inclinations. None of these crustal elements has been rotated to account for anomalous declinations. The northward displacements were accommodated on the Baja B.C. and Intra-Quesnellia faults, shown in red. Baja British Columbia includes a western sliver of the Insular superterrane, the Baja Alaska of Stone, Panuska, and Packer (1982), that presently lies northwest of the Chatham Strait fault (compare the disposition of the superterrane in fig. 1). Its paleolatitude at 90 Ma is based on the MC data set in table 1. In (B), the MS and MT paleomagnetic localities are closer together than in figure 1 because 160 km of Cenozoic dextral slip on the Fraser-Straight Creek fault has been removed.

The Baja British Columbia Hypothesis: Rocks that are now in British Columbia formed off the coast of NW Mexico, at the latitude of Baja California. They drifted east, docked with North American continent between 100 and 80 mya, and then slid northward between 80 and 50 mya along great system of faults to present location in Canada.

	Evidence **for** Baja British Columbia Hypothesis	Evidence **against** Baja BC hypothesis
General picture:	Terranes that are now British Columbia originally formed at latitude of Baja California, then were translated northward 1000 to 3000 km to present location	Terranes that are now British Columbia formed off coast of Canada, and were accreted onto North America at same latitude
Paleomagnetic inclinations: show what latitude blocks are formed at	Paleomagnetic inclinations in coastal BC are shallower than inland, suggest formed 3000 km to south 95 million years ago	This assumes that the orientation of plutons hasn't changed since formation; more likely, blocks have been tilted by geologic processes, making magnetic inclinations shallow
BUT:	Paleomag folks adjusted for tilting of warped sedimentary and volcanic layers (originally flat when emplaced), got consistent values for magnetic inclination which are still shallow	
The fault		where is the fault? geologists see no evidence of fault in the area, therefore no room for lots of displacement
BUT:	Paleomag folks suggest that the fault could have been obliterated by younger plutons, or reactivated as a dip-slip fault, or removed by crustal extension	geologists doubt that the fault would be so deformed that they couldn't find it
marine fossils: if rocks formed far to south, would expect warm-water mollusks and microfossils in rocks		most of 145 to 100 myr old fossils in rocks are characteristic of temperate and northern latitudes, suggesting that rocks formed at present latitude
zircon grains in sediment: if formed near mexico, expect to be 1 gyr old, but if formed near BC, expect 2 gyr old		grain ages older than Mexico, consistent with position 500 to 1000 km to S, not 3000 km to S
The hit and run theory of formation of the Rockies (Laramide Orogeny): Resembles orogenies due to plate collisions elsewhere, but where's the plate?	Laramide orogeny could have been caused by plate collision / translation as Baja British Columbia slid northward along western coast of US - same time frame, consistent with structure of rifting etc. on Baja British Columbia	Shallow slab subduction beneath western NA plate caused crustal block uplifts and magmatism, creating the Laramide Orogeny

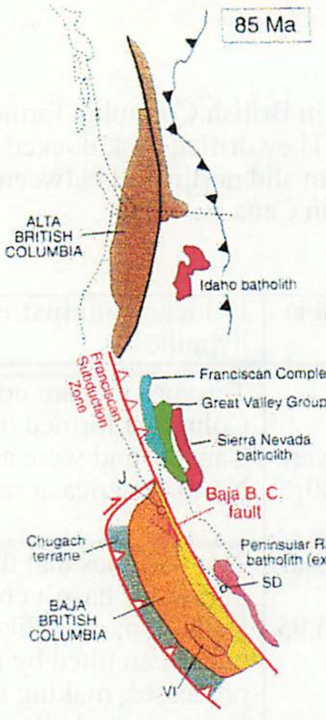


Fig. 4. Hypothetical four-stage displacement history for Baja British Columbia and Alta British Columbia. The present geographic positions of the Idaho batholith, the eastern limit of the Cordilleran thrust belt, Vancouver Island, and the international boundaries of the United States are as they appear in figure 1. Colors used for crustal elements are the same as those in figures 1 and 2, except extinct batholiths are shown in light red. Red lines with barbs are inferred active convergent plate boundaries (subduction zones); solid red lines are hypothetical active transform boundaries, including continental transform faults. (A) 85 Ma. Northward coastwise displacement of Baja British Columbia began no earlier than this time. This figure is basically the same as figure 2B, but certain elements in the latter have been deleted. The subduction zone west of Baja British Columbia was active before and at 85 Ma and gave rise to the magmatic arc in the Coast Mountains and to the subduction complex in the Chugach terrane. Baja British Columbia is inferred to have been accreted to North America along the southern extension of the Franciscan subduction zone, which progressively changed into the Baja B.C. transcurrent (transform) fault, possibly as a triple junction at the northern end of Baja British Columbia migrated northward. Arc magmatism east of the transform was extinguished.

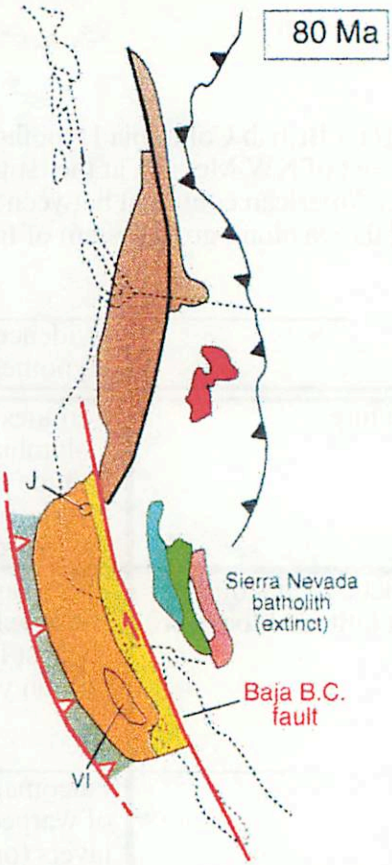


Fig. 4(B) 80 Ma. Baja British Columbia lay immediately west of the extinct Franciscan-Sierran system in present-day California.

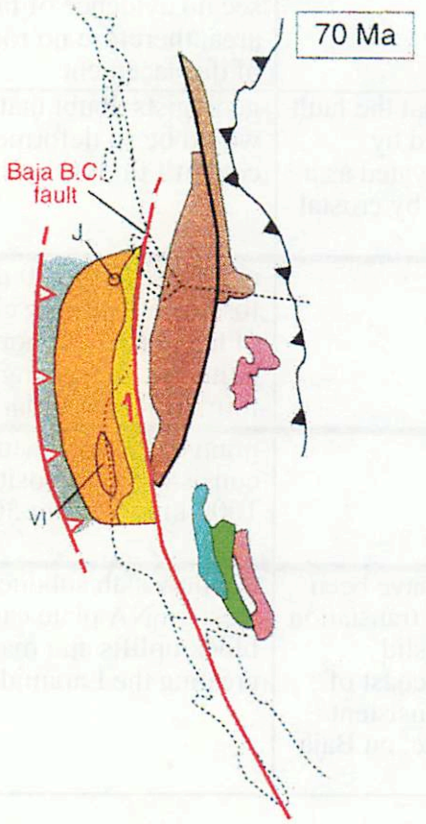


Fig. 4(C) 70 Ma. Baja British Columbia lay mostly north of California and had arrived in its present position relative to Alta British Columbia (the western two-thirds of the Intermontane superterrane). Plutonism in the Coast Mountains and accretion in the Chugach terrane record continued subduction beneath Baja British Columbia.

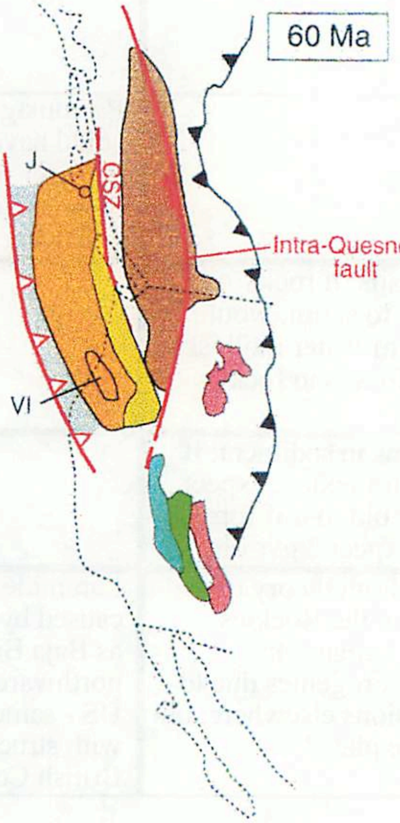


Fig. 4(D) 60 Ma. The composite crustal element consisting of Baja and Alta British Columbia begins to move northward along the Intra-Quesnellia fault. The Coast Shear Zone (CSZ), which is roughly coextensive with the now extinct Baja B.C. fault, experiences active dip-slip at this time.

References

Atwater, T., 1989, Plate tectonic history of the northeast Pacific and western North America, *in* The Eastern Pacific Ocean and Hawaii (eds. E.L. Winterer, D.M. Gussong, and R.W. Decker), Boulder, Colorado, Gological Society of America, Geology of North America, v.N, pp. 21-72.

Cowan, D.S., M.T. Brandon, and J.I. Garver, 1997, Geologic Tests of Hypotheses for Large Coastwise Displacements - A Critique Illustrated by the Baja British Columbia Controversy, American Journal of Science, v. 297, pp. 117-173.

Filmer, P.E., and J.L. Kirschvink, 1989, A Paleomagnetic Constraint on the Late Cretaceous Paleoposition of Northwestern Baja California, Mexico, JGR, v. 94 #B6, pp. 7332-7342.

Hagstrum, J.T., M. G. Sawlan, B.P. Hausback, J.G. Smith, and C.S. Gromme, 1987, Miocene Paleomagnetism and Tectonic Setting of the Baja California Peninsula, Mexico, JGR v. 92 #B3, pp. 2627-2639.

Humphreys, E.D. and R.J. Weldon, 1991, Kinematic constraints on the rifting of Baja California, *in* The Gulf and Peninsular Provinces of the Californias (eds. J.P. Dauphin and B.R.T. Simoneit), American Association of Petroleum Geologists Memoir 47, pp. 217-229.

Kerr, R.A., 1995, How Far did the West Wander?, Science v. 268, pp. 635-637.

Lonsdale, P., 1989, Geology and tectonic history of the Gulf of California, *in* The Eastern Pacific Ocean and Hawaii (eds. E.L. Winterer, D.M. Gussong, and R.W. Decker), Boulder, Colorado, Geological Society of America, Geology of North America, v.N, pp. 499-521.

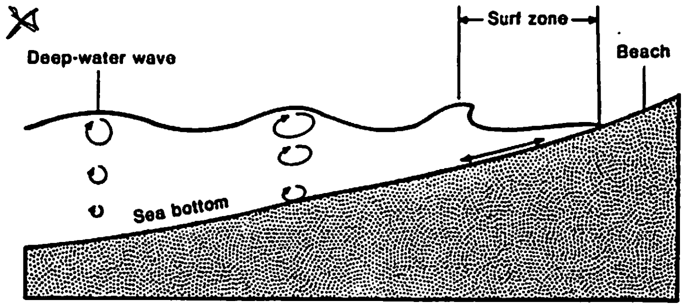
Lund, S.P. and D.J. Bottjer, 1991, Paleomagnetic evidence for microplate tectonic development of southern and Baja California, *in* The Gulf and Peninsular Provinces of the Californias (eds. J.P. Dauphin and B.R.T. Simoneit), American Association of Petroleum Geologists Memoir 47, pp. 231-248.

Maxson, J., and B. Tikoff, 1996, Hit-and-run Collision model for the Laramide Orogeny, Western United States, Geology, v. 24, #11, pp. 968-972.

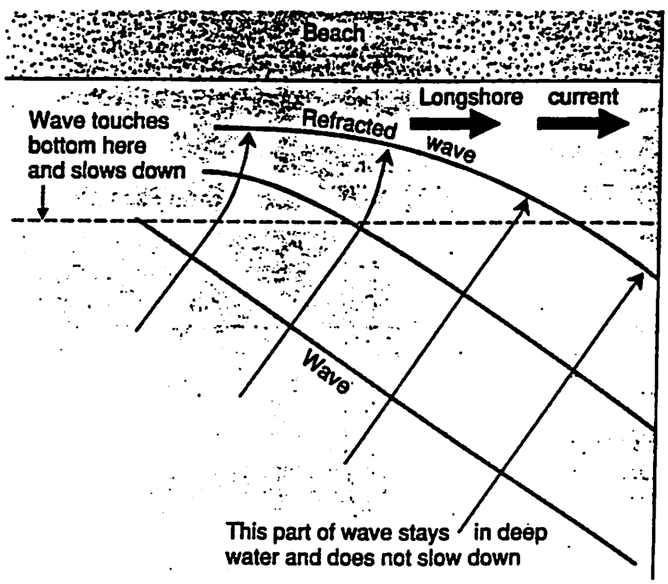
Morris, L.K., S.P. Lund, and D. J. Bottjer, 1986, Paleolatitude drift history of displaced terranes in southern and Baja California, Nature, v. 321, pp. 844-847.

Umhoefer, P.J., R.J. Dorsey, P. Renne, 1994, Tectonics of the Pliocene Loreto basin, Baja California Sur, Mexico, and evolution of the Gulf of California, *Geology*, 22, pp. 649-652.

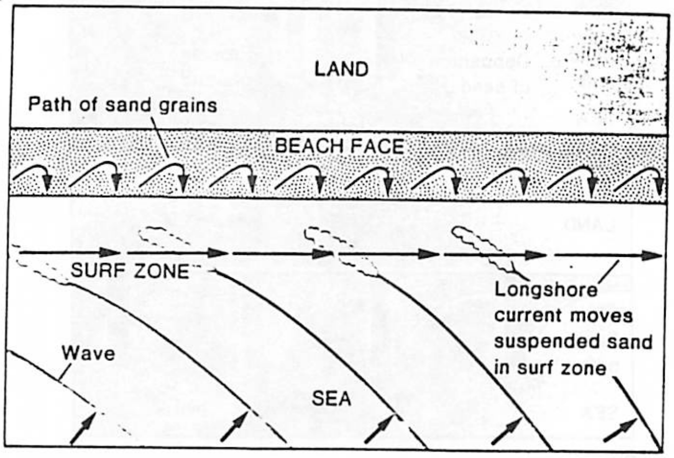
Umhoefer, P.J., 1987, Northward Translation of "Baja British Columbia" along the Late Cretaceous to Paleocene Margin of Western North America, Tectonics, v. 6 #4, pp. 377-394.



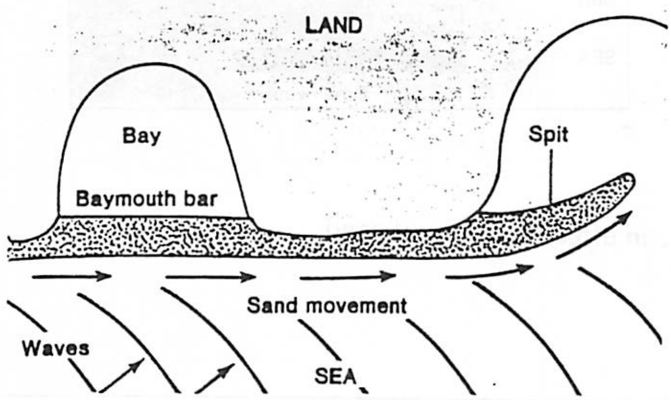
Wave action in deep water resembles circular orbits which dampen with depth. Most of this circular motion has died out at a point where the depth reaches half the wave length of the surface wave. The wave begins to feel the sea bottom as the water shallows causing the circular orbits to flatten until only onshore and offshore motion remains.

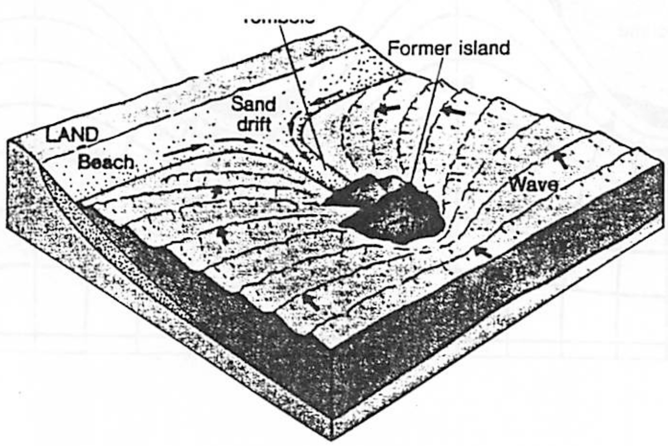


If waves approach perpendicular to the shore a grain of sand on the beach would move back and forth, onshore and offshore. Waves that approach the shore at an angle create a longshore current that runs parallel to the shoreline. This current allows a net movement of sand grains in the direction of the induced current.



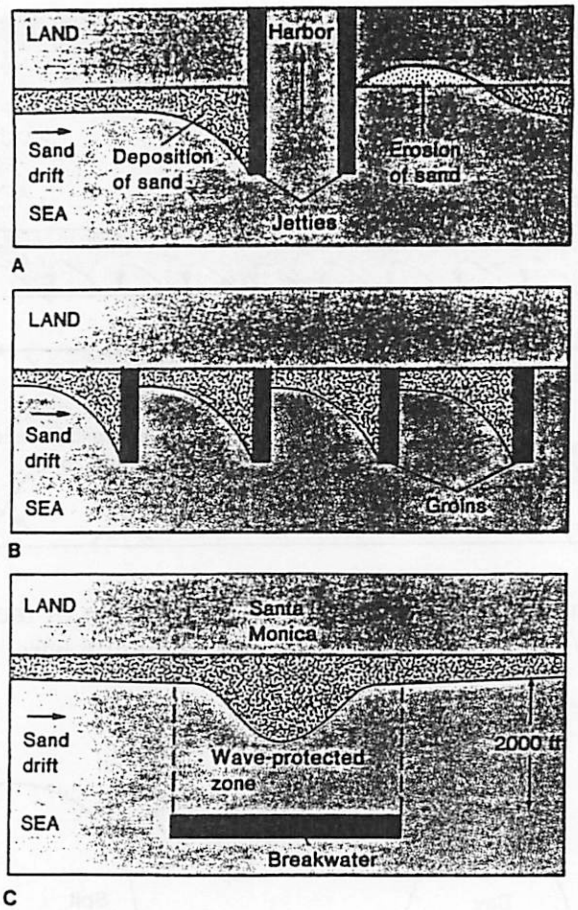
Sand grains move in a zig-zag pattern along the direction of the longshore current. This longshore drift carrying sand can form spits and baymouth bars.



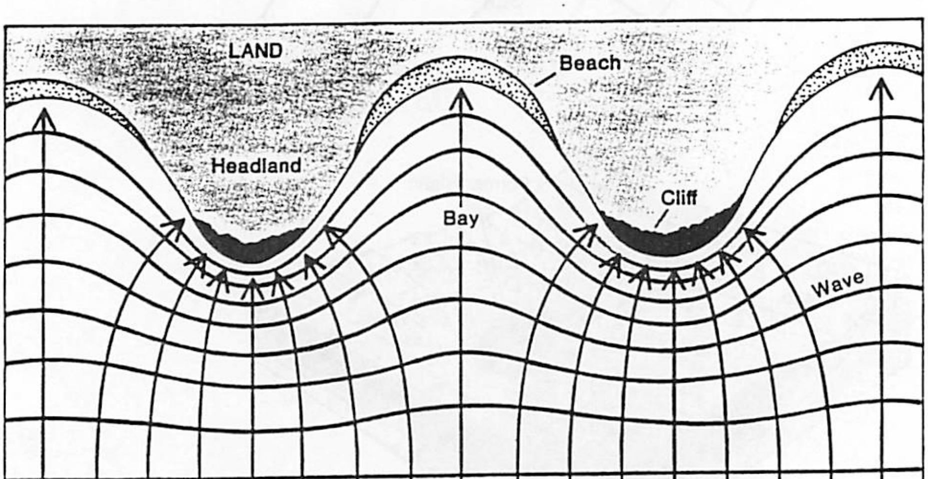


A

Islands can act to refract waves which induces longshore transport of sand directly behind them which over time can build up a tombolo.



Man made objects can effect the flow of sand.



Irregular coast lines produce wave refraction that deposits eroded material on beaches in bays. This eroded material comes from the headlands where erosion takes place.

If I were a Cephalopod ®

The story of the Ammonites: Late Devonian - Upper Cretaceous

Taxonomy.

As a quick review of Freshman biology, lets first take a look at taxonomy. Running from the broadest to the most general, the classification scheme is: Phylum, Class, Order, Family, Genus, Species. This can be peppered with Super's and Sub's to account for groups not large enough to warrant a new division. Example of what we may see today:

Phylum Mollusca
Class Cephalopoda
Subclass Ammonoidea
Order Ammonitida
Superfamily Goniatitina
Family Goniatitaceae, etc.

Phylum Mollusca

This phyla contains critters that are most favored in Boston, those that go crunch when you're wandering barefoot at night, and those that attack and devour submarines. Figure 1, depicts the many classes of Molluscs including: Bivalvia (clams), Gastropoda (snails), and Cephalopoda (squid, octopi, and ammonites!). Due to the similarities of their internal organs, the Molluscs are thought to have evolved from a single common ancestor (other than the LCA) not yet found in the fossil record.

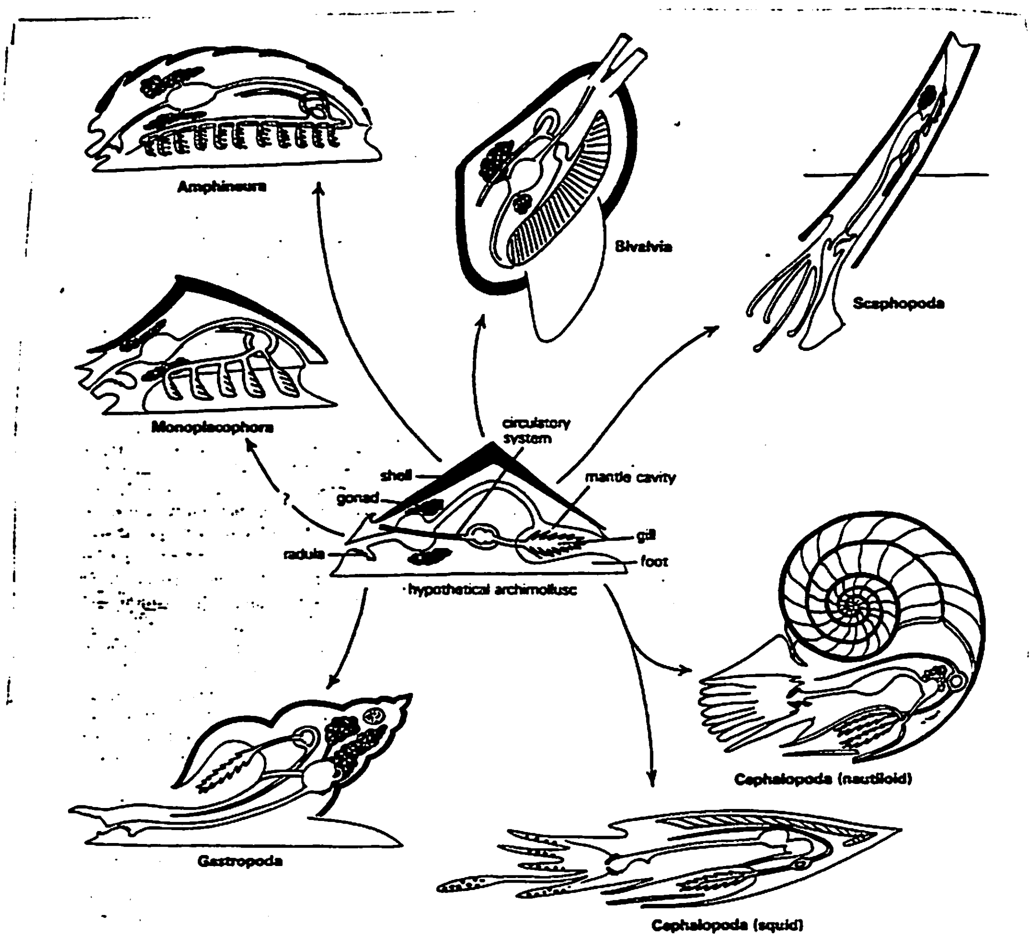


Figure 1. Phylum Mollusca

Class Cephalopoda

The Cephalopods (headfeet) include three Subclasses: Colieoidea, Nautiloidea, and Ammonoidea. The Colieoids have an internal shell. Examples are squids, octopi, and cuttlefish.. The Nautiloids have a coiled or straight external shell. To first order Ammonites differ mainly in that their external shells are always coiled.

Nautiloids vs. Ammonoids

First a crash course in Cephalopod Anatomy.

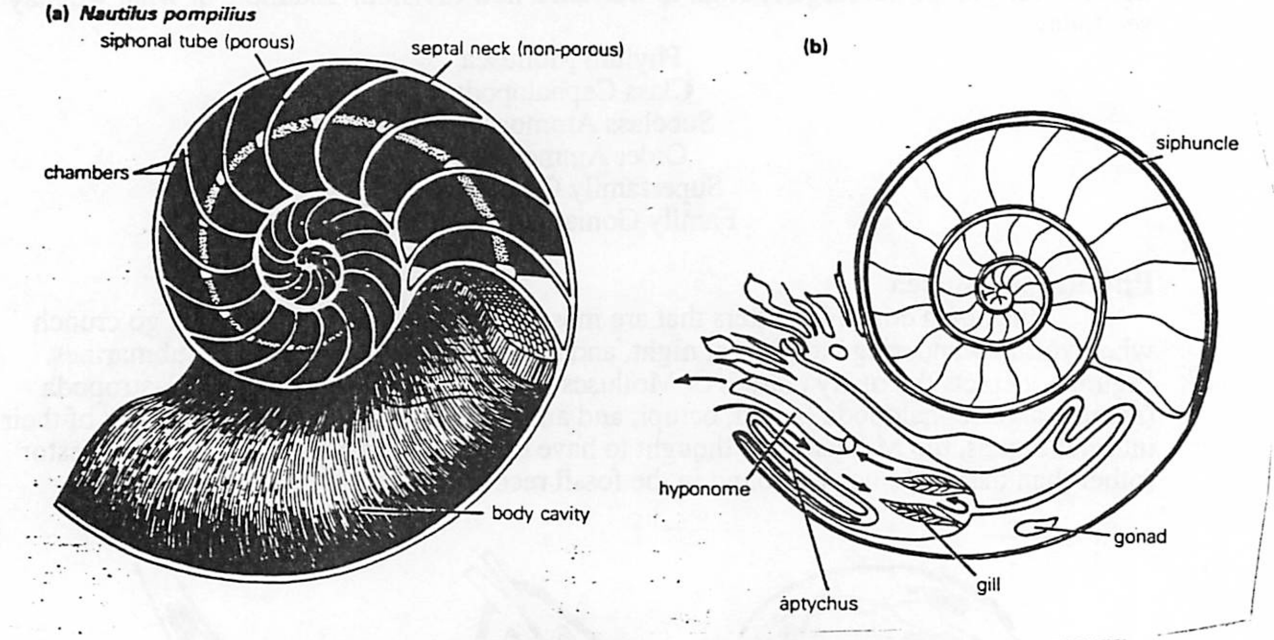


Figure 2. Nautiloids vs. Ammonites

The interior of the shell is made up of a series of chambers called **camerae**. They are connected by a single tube called a **siphuncle**. The walls enclosing the camerae are called **septa** (sing. **septum**). Where the septa intersect with the shell they produce a pattern called **suture**. Some of the internal organs are depicted in part b of Figure 2, including the gills, gonads, and the hyponome. The **hyponome** is a short tube that the cephalopod uses for propulsion by squirting water out, similar to the caterpillar drive in Hunt for Red October.

The main differences between Nautiloids and Ammonites is the location of the siphuncle and the suture pattern. All nautiloids have their siphuncle located centrally, as seen in Figure 2a. Wow, you're actually reading my handout. Most ammonites have their siphuncles positioned on the ventral, or on the outside of the shell, as seen in Figure 2b. Some have them located on the dorsal side, but those are rare. Nautiloids tend to have a very simplistic suture pattern, while those of Ammonites can be very complex.

Evolution of Suture Patterns (or How to Build a Better Submarine)

There are three main types of suture patterns, ranging from simple to complex, Figure 3. The simplest is **goniatitic** which consists of smooth saddle and pointed lobes. **ceratitic** suture is the same, except that the cusps are jagged. I'm not even going to try to describe **ammonitic** suture, since you can take a look at it yourself in Figure 3c.

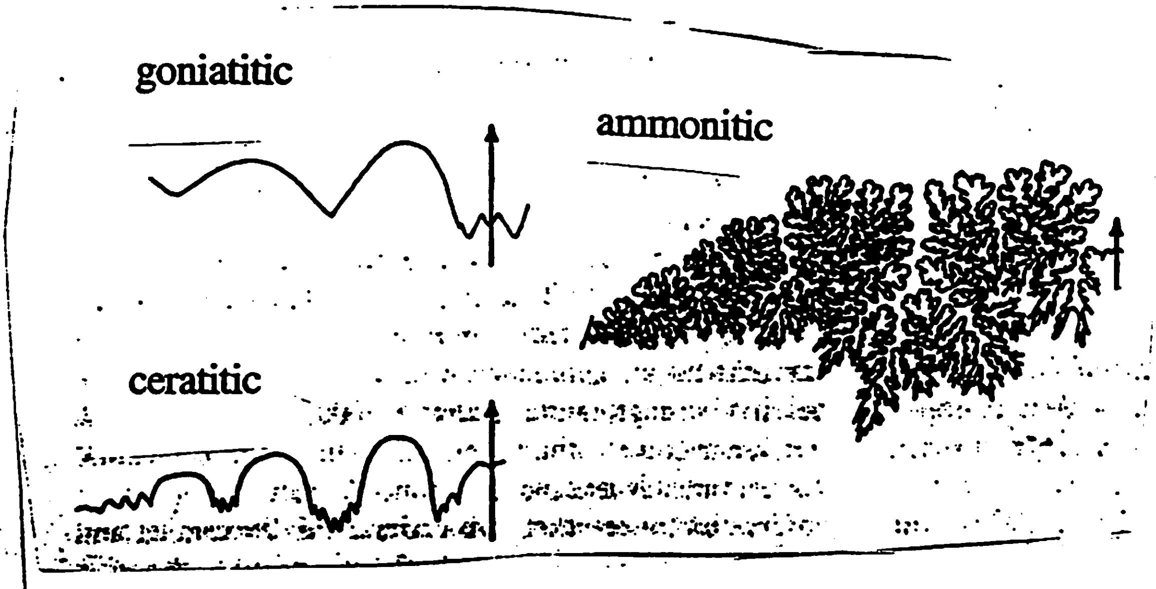


Figure 3. Types of Suture

The ammonites didn't spend their existence generating these pretty patterns so that the Nature Company could make a buck. No, in the days before capitalism things had to be useful. The more complex the suture pattern, the more support from the septa, and thus, the stronger the shell. The stronger the shell, the deeper the ammonite can swim without imploding. Exact numbers on the strength of the shells are unfortunately unavailable, since the actual shell material is generally replaced during fossilization.

Paleontologists are still debating about such characteristics as sexual dimorphism. Generally the jury is still out, since the ammonites are, alas, extinct, and can only be compared to the modern Nautilus. But that's OK, since we're sure to see the ammonites in hell.

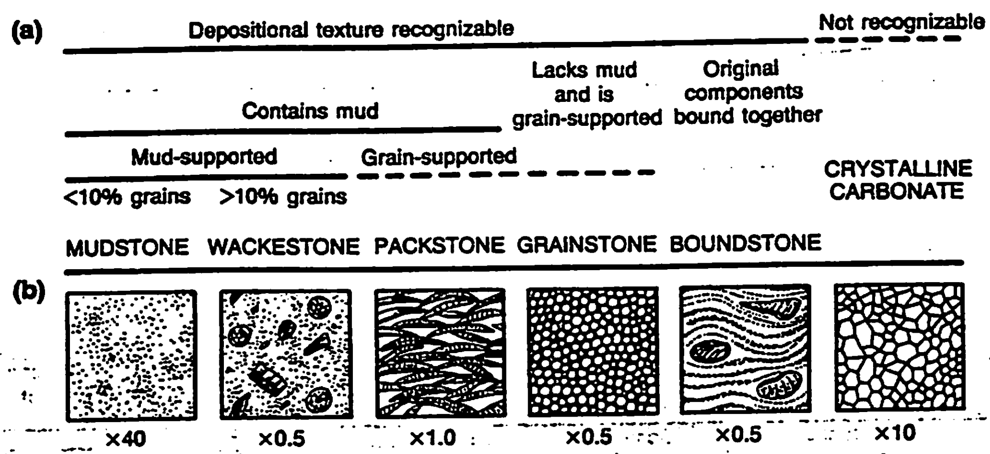
References

Clarkson, E. N. K, Invertebrate Paleontology and Evolution, Chapman & Hall, London, 1993.

Raup, D. M., and Stanley, S. M., Principles of Paleontology, W. H. Freeman and Company, New York, 1978.

Limestone Petrology (all you'll ever want to know) ®

The carbonates are broken up into two main groups: limestone, which is made of Calcite ($CaCO_3$) and dolostone, which is made of dolomite ($MgCO_3$). These rocks are generally classified by the type and texture of their **allochems**. Allochems are bits of pre formed rock. They include fossils, **oolites** (spherically layered carbonates), organics, and precipitates. Classification systems differ in what they think is important. The **Dunham system** looks at depositional texture. The **Folk system** recognizes four materials: allochems, microcrystaline ooze (**micrite**), crystalline calcite (**sparite**), and fossiliferous reef rock (**biolithite**). The **Cuffey system** is something of a meld of the two. If you have any questions talk to my petrology book.



(c)

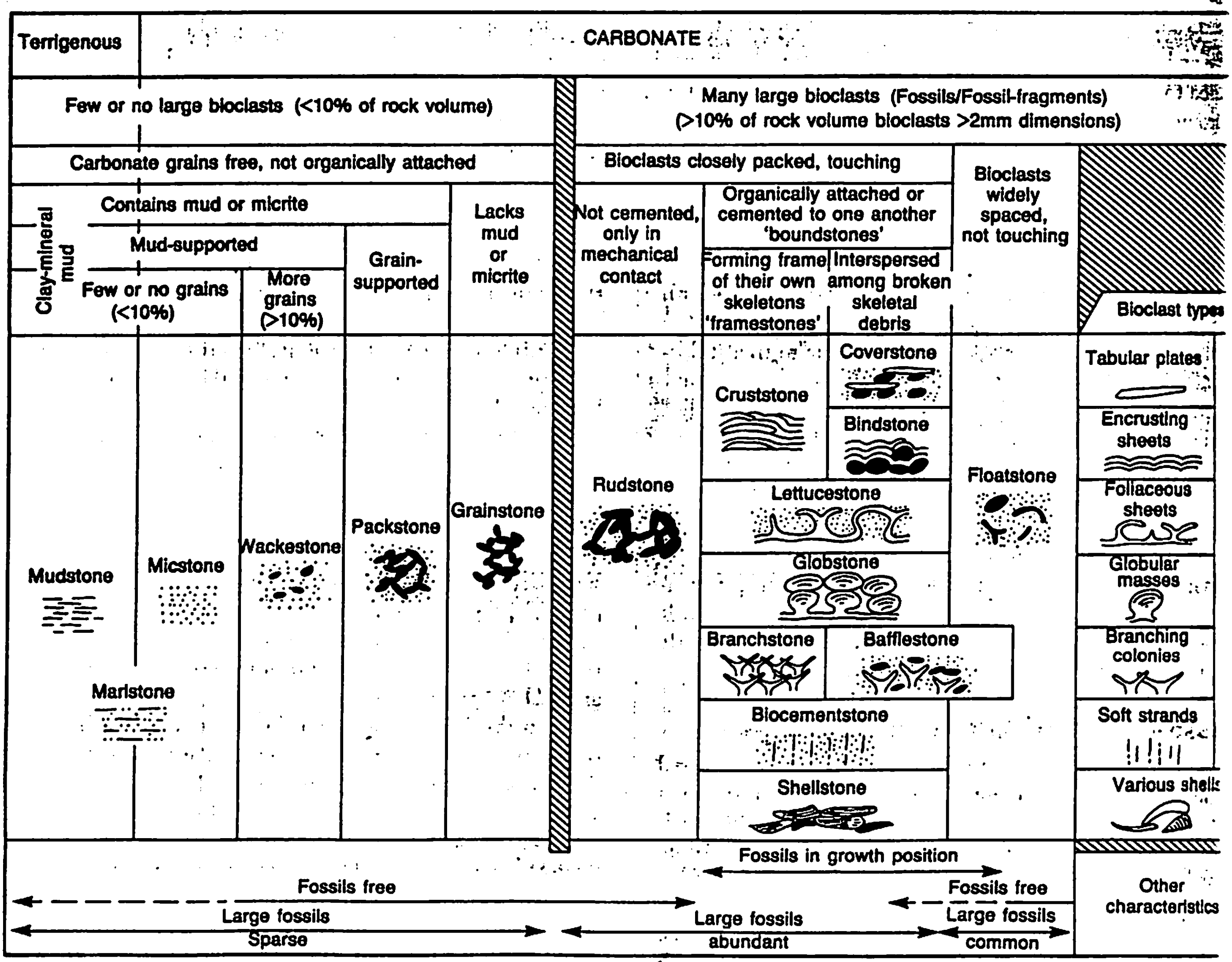
Predominantly calcite (Cc >95%)	Dominantly calcite (95%>Cc>50%) with dolomite	Dominantly dolomite (Do >50%)	Thoroughly recrystallized rocks with some relict structures: Dominantly dolomite	Thoroughly recrystallized rocks with some relict structures: Dominantly calcite
Lime mudstone	Dolomitic lime mudstone	Dolomudstone		
Wackestone	Dolomitic wackestone	Dolowackestone	Crystalline dolostone	Crystalline limestone
Packstone	Dolomitic packstone	Dolopackstone		
Grainstone	Dolomitic grainstone	Dolograinstone		
Boundstone	Dolomitic boundstone	Doloboundstone		

Dunham Classification

Folk Classification

Volumetric allochem composition	Limestones, partially dolomitized limestones, and primary dolomites (see Notes 1 to 6): >10% Allochems, Allochemical rocks (I and II): Sparry calcite cement > microcrystalline ooze matrix — Sparry allochemical rocks (I)	>10% Allochems: Microcrystalline ooze matrix > sparry calcite cement — Microcrystalline allochemical rocks (II)	<10% Allochems, Microcrystalline rocks (III): 1-10% allochems	<10% Allochems: <1% allochems	Undisturbed bioherm rocks (IV)	Replacement dolomites (V) (see note 7): Allochem ghosts	Replacement dolomites: No allochem ghosts
<25% Intraclasts (I)	Intrasparrudite (Ii:Lr) Intrasparite (Ii:La)	Intramicrudite* (IIi:Lr) Intramicrite* (IIi:La)	Most abundant allochem — Intraclasts: intraclast-bearing micrite* (IIIi:Lr or La)	Micrite (IIIm:L); if disturbed, dismicrite (IIImX:L); if primary dolomite, dolomicrite (IIIm:D)	Biolithite (IV:L)	Evident allochem — Finely crystalline intraclastic dolomite (Vi:D3) etc.	Medium crystalline dolomite (V:D4)
<25% Intraclasts; >25% Oolites (O)	Oosparrudite (Io:Lr) Oosparite (Io:La)	Oomicrudite* (IIo:Lr) Oomicrite* (IIo:La)	Oolites: oolite-bearing micrite* (IIIo:Lr or La)			Coarsely crystalline oolitic dolomite (Vo:D5), etc.	Finely crystalline dolomite (V:D3)
<25% Intraclasts; <25% Oolites; Volume ratio of fossils to pellets >3:1 (b)	Biosparrudite (Ib:Lr) Biosparite (Ib:La)	Biomicrudite (IIb:Lr) Biomicrite (IIb:La)	Fossils: fossiliferous micrite (IIIb:Lr, La, or L1)			Aphanocrystalline biogenic dolomite (vb:D1), etc.	
<25% Intraclasts; <25% Oolites; Volume ratio of fossils to pellets 3:1 to 1:3 (bp)	Biopelsparite (Ibp:La)	Biopelmicrite (IIbp:La)	Pellets: pelletiferous micrite (IIIp:La)			Very finely Crystalline pellet dolomite (Vp:D2), etc.	etc.
<25% Intraclasts; <25% Oolites; Volume ratio of fossils to pellets <1:3 (p)	Pelsparite (Ip:La)	Pelmicrite (IIp:La)					

Cuffey Classification



Introducing the

LPL Field Trip Song Book

First Edition

In observance of our first visit to Baja, I thought it appropriate for the group to learn one of Mexico's best known songs. I also didn't want to hear La Cucaracha.

Cielito Lindo

Quirino Mendoza y Cortes
trans. some guy on the web
Sung to the tune of "Cielito Lindo"

De la Sierra Morena,
Cielito lindo, vienen bajando
Un par de ojitos negros,
Cielito lindo, de contrabando

Coro:
Ay, ay, ay, ay,
Canta y no llores,
Porque cantando se alegran,
Cielito lindo, los corazones

Pajaro que abandona,
Cielito lindo, su primer nido,
Si lo encuentra ocupado,
Cielito lindo, bien merecido
Coro:

Ese lunar que tienes,
Cielito lindo, junto a la boca,
No se lo des nadie,
Cielito lindo que a mi toca
Coro:

Si tu boquita, morena
Cielito lindo, fuera de azucar,
Yo me lo pasaría,
Cielito lindo, chupa que chupa
Coro:

De tu casa a la mía,
Cielito lindo, no hay más que un paso,
Ahora que estamos solos,
Cielito lindo, dame un abrazo.
Coro:

From the dark mountains, my darling,
You look down on me, my pretty sky.
O your dark eyes make my heart sing
Pretty sky, so lovely that I could die.

Chorus:
Ay, ay, ay, ay,
Sing, and don't cry,
Because singing, it makes the spirits high
And makes the heart glad, my pretty sky.

A restless bird that leaves it's nest,
To take wing and to fly, pretty sky,
May find that it can never rest,
Pretty sky, once it says goodbye.
Chorus:

That beauty mark that you have on,
Your dark mountainous lip, pretty sky,
O, please let it never be gone,
Pretty sky, because it's mine till I die.
Chorus:

Your brown mountain mouth, seemed
Sweeter than sugar, seen in my fond gaze
Could I but taste and never weaned,
Pretty sky, I'd be content all my days.
Chorus:

From your house to mine does wind
Only one road, my pretty, pretty sky.
If on our private path we find,
Each other, in your arms I will fly.
Chorus:

The Chicxulub Impact Crater and the K/T Boundary Layer

Impact Theory, What to look for, and What you'd see if you really found it

brought to you by your hostess with neuroses, **Jennifer A. Grier**
and your hostess with the steel tire jack, **Nancy Chabot**

I. Impact, Climate Changers, and stuff that might ruin your day

The "approximately circular geophysical anomaly" that is now considered to constitute the Chicxulub crater was identified by oil drilling surveys conducted in the 50's. The structure lies on the very northern edge of the Yucatan peninsula, and seismic, gravity and magnetic data suggest that the best estimate for the diameter of the feature is 180 km (this point has been debated). Crystalline melt rock and polymict breccia (from the carbonate platform overlain by about 1 km of Tertiary sediments) have been recovered by the drilling. 40Ar/39Ar dating has been conducted on melt samples from the structure, which appear indistinguishable from impact glasses obtained from Mexico and the Caribbean (~ 65 Ma). The controversy surrounding the identification of this structure as an impact crater, and other areas of contention will be discussed by Betty.

Thus it is generally believed that the formation of the crater began ~65 Ma ago, when a body impacted the shallow sea (< 100 m depth) then extant over the northern peninsula region of the Yucatan. Under the sea was a thick sequence of carbonates (limestone and some dolomite) and evaporites (anhydrite $CaSO_4$ and some gypsum $CaSO_4 \cdot 2H_2O$). Estimates range from 50-50, to 70% carbonate, 30% evaporites. The impact explosion energy was a massive 1E8 megatons, ejecting material out from a depth of 13 to 15 km and displacing material at about 40 km depth. The best estimates for the transient crater diameter are 90 to 105 km. The final crater appears to be a complex, probably multi-ring basin with a possible central peak or even a central ring.

It is quite probable that the Chicxulub impact event was responsible for a dramatic global climate change 65 Ma ago, as well as local devastation. The amount of thermal radiation produced by the impact would have ignited forests; thereby destroying local ecosystems and adding more smoke and dust to the atmospheric mix. Tsunamis are also predicted, and supposedly some evidence for their occurrence at the K/T boundary exists in some Gulf sites in Mexico. Blast waves, and at a greater distance atmospheric overpressure would have flattened local plants and killed animals instantaneously. Even a much smaller impact, like meteor crater, was responsible for widespread devastation of the local area, and no doubt, the extermination of much local flora and fauna.

An increase of 20% CO_2 in the atmosphere has been predicted, but would probably not have been the driving factor for climate change. This increase in CO_2 would probably have caused an increase in the overall temperature of only 1.2 °C. Conversely, Chicxulub might have liberated enough S bearing gases (SO_2 or SO_3) to depress world temperatures more than 5 °C for several years or even decades. S and water pumped into the atmosphere by the impact might have combined to form stable, long lasting sulfate aerosol particles, which appear to be very effective at blocking sunlight from the surface. Because of this, it appears that the target lithology of a very big impact like Chicxulub is of great importance in ascertaining the effect of the impact on the climate. If the impact had occurred into different rocks, the effect may have been quite different. The angle of the impact may also be an important factor. Some studies indicate that oblique impacts may vaporize more of the surface layers than more vertical impacts. While acid rain has been shown to be an expected product of the impact event, it is not clear if the pH levels of sea water would be effected enough to cause and mass extinctions.

II. What to Look for at the Site (also how to get there and how to find what we are interested in)

Some food for thought, given how much rain we've had ... "We just came back from our Baja trip, and we did actually manage to visit the locations at San Antonio Del Mar. There was a massive rainstorm last week, which wiped out the main road to the beach along that section, but we were able to drive down to the coast village right near the K/T section and walk in from there. **It was 4WD most of the way, slipping and sliding in mud**... (Joe Kirschvink)" Yeehah!

First, we need to actually get to the field stop, and then we need to do our best to constrain the location of the K/T boundary layer we are interested in. We have GPS coordinates to help us get in to the K/T field stop, and to help us find the locations of the two critical fossil localities on the beach which constrain the position (Paleocene gastropods, and upper Maastrictian ammonites) of the K/T section.

Directions and GPS coords to the K/T field stop:
W SADM01 N31 04.56989' W116 12.53012' (This is the turn off from the main highway #1 into the Plya San Antonio Del Mar). Take the road up the hill and in towards the coast.

W SADM02 N31 05.64009' W116 17.22002' (this is a Y-junction - take the left-hand road, towards SADM03)

W SADM03 N31 05.04014' W116 18.22006' (Another Y-junction - take the south road, up the hill towards the cliff overlooking the beach. Follow this road south to the small village perched on the sea cliffs - there are several vacation homes under construction. Drive down the almost-washed-away road, and park nearby. DO NOT try to drive down to the beach -- the road is washed away.) There is a reasonably flat area to camp in, if desired. Walk down the road to the main wash that has access to the beach.

Beds at this locality dip gently to the South, and it is possible to trace units around to the fresh exposures on the beach, where most of the fossils are. The highest Masstrictian ammonite located so far is North of the wash entrance to the beach at GPS coordinates at:
W AMONIT N31 05.10194' W116 18.92140'
The early Paleocene turatella gastropod locality is South of the wash entrance to the beach GPS of: W TURITL N31 04.29985' W116 19.11001'

Unfortunately, the critical interval which must contain the K/T boundary is not exposed on the beach, being covered by Qal. However, we can begin by looking for the gastropods on the beach which are in a characteristic claystone / mudstone facies with yellow (sulfurous) banding, just below a facies change to more sandy, light weathering unit. This caps the cliff face on the North side of the wash, and can be seen in the exposures on the South face of the wash as well, just inland from the beach. The ammonite position can be correlated southwards to the wash based on some thick carbonate concretions, with characteristic orange carbonate veins inside them; this is clearly visible in the lower part of the cliff. (Note the real 'cliff' is near the top of the wash section - you can scramble up the small erosion gullies to examine the section between the two constraints there.)

After we have constrained the location of the K/T boundary between the gastropods and ammonites, we need to closely examine the interval between these boundaries, and see if we convince ourselves that the K/T boundary is there, and if any sign of the impact layer(s) is there. We will probably be looking in and around the Ballenas Formation. At the base of this formation should be a conglomerate which contains the K/T rock area we are interested in. Given the distance from the impact site in the Yucatan, we might expect the thickness of the deposit to be much like that identified in Colorado. There the K/T impact layer is about 1 cm thick. We should be looking for a clay stone of a different color, or perhaps a pebbly conglomerate which might indicate seismic slumping of the material. Both of the two layers described in section 1 may not be identifiable, since a conglomerate or seismic slumping might wipe out a layer(s).

III. What you'd see if you really found it

The K/T boundary sequence is composed of two layers at locations within about 5000 km of Chicxulub crater. These two layers correspond to low and high energy ejecta. The bottom of the two layers is the low energy ejecta, the thickness of which drops off steeply with increasing distance

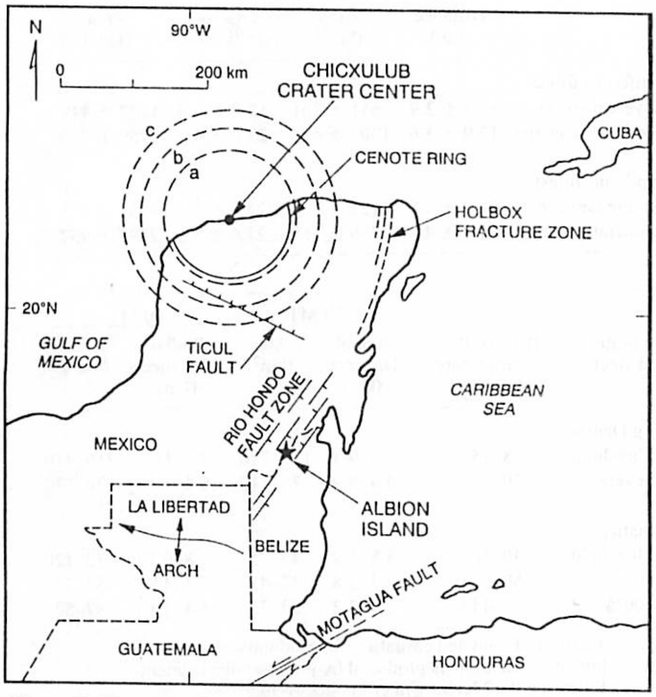


Figure 1. Map showing the location of Albion Island, Belize, with respect to the buried Chicxulub impact crater and other geological structures of the region. Dashed circles represent proposed crater diameters: (a) 180 km (Hildebrand et al., 1991; Pilkington et al., 1994), (b) 240 km (Pope et al., 1993), and (c) 300 km (Sharpton et al., 1993).

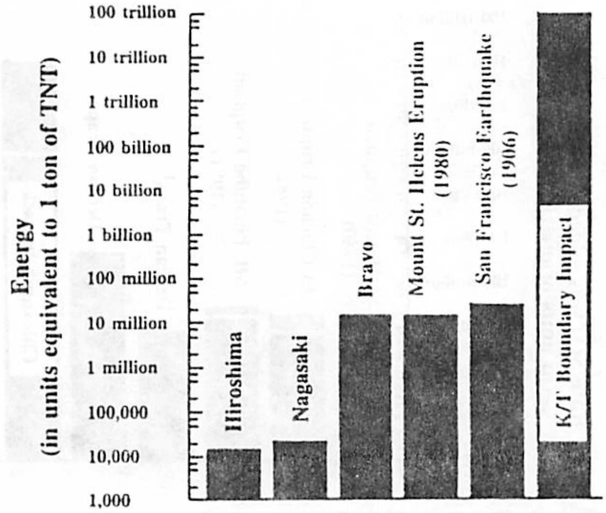


Figure 5. The energy of the K/T boundary impact event compared to several other geologic events and nuclear explosions, including Bravo, the United States' largest nuclear test explosion (DOE, 1991; Friedman et al., 1981; Bullen and Bolt, 1985; Morrison, 1992).

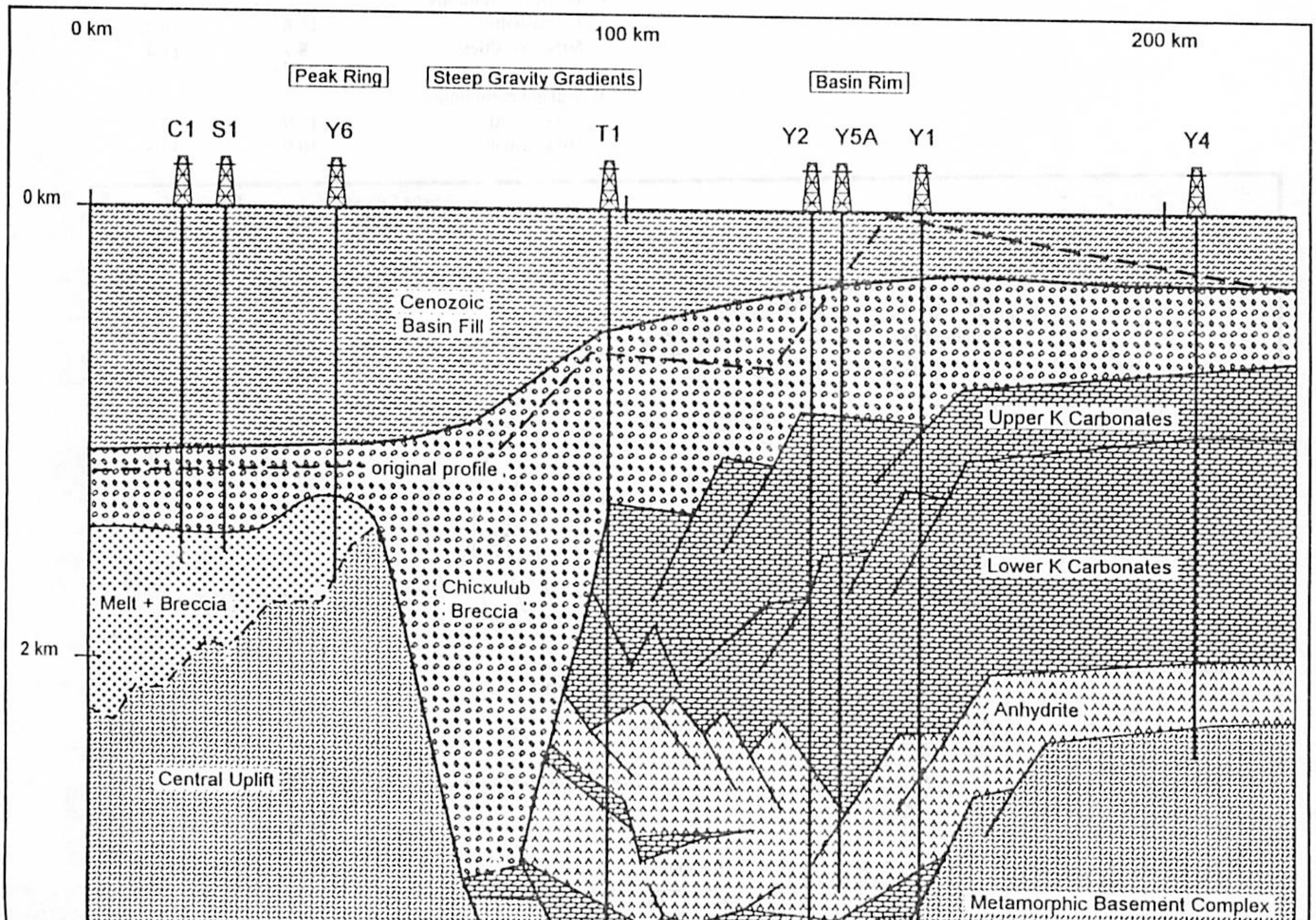


Figure 5. Schematic model of the Chicxulub impact basin that we derive from the analysis in this chapter. This simplified cross section shows the generalized present-day configuration of the crater consistent with geophysical data and well information. Erosion at the time of impact could rearrange the upper crater units significantly and reduce crater topography. Original profile shown as dashed line is reconstructed from the generalized topographic profile of the 270-km Mead Basin on Venus (Fig. 6).

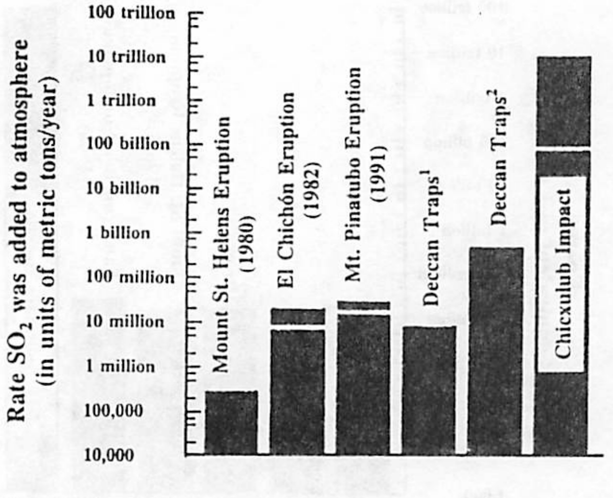


Figure 8. The rate at which SO_2 vapor is added to the Earth's atmosphere during the Chicxulub impact and several other geologic events. The first estimate for the Deccan Traps assumes volcanism occurred over a 600,000 year interval, while the second assumes a 10,000 year interval. (Data for the volcanic events are from Officer et al. (1987), Rampino et al. (1988), Brasseur and Granier (1992). Data for the Chicxulub impact are from Sigurdsson et al. (1992), Brett (1992), and this study.)

	20 MT		40 MT	
	Distance (km)	Area (km^2)	Distance (km)	Area (km^2)
Coniferous forest				
Severe damage	14.4 ± 2.9	651 ± 261	18.9 ± 3.8	1122 ± 449
Moderate damage	17.9 ± 3.6	1007 ± 403	23.6 ± 4.7	1750 ± 700
Deciduous forest				
Severe damage	18.9 ± 3.8	1122 ± 449	24.8 ± 5.0	1932 ± 773
Moderate damage	21.1 ± 4.2	1399 ± 559	27.6 ± 5.5	2393 ± 957

		20 MT		40 MT	
Biological Effect	Effective Peak Overpressure (psi)	Radial Distance (km)	Area (km^2)	Radial Distance (km)	Area (km^2)
Lung Damage					
Threshold	8–15	6.5–9.3	130–270	8.1–11.7	210–430
Severe	20–30	4.9–5.9	75–110	6.2–7.4	120–170
Lethality					
Threshold	30–50	3.8–4.9	45–75	4.8–6.2	72–120
50%	50–75	3.2–3.8	32–45	4.1–4.8	52–72
100%	75–115	2.7–3.2	23–32	3.4–4.1	37–52

TABLE 4. Estimated casualties for randomly oriented human-sized animals produced by physical displacement following the Meteor Crater impact event.*

	20 MT Radial Distance (km)	40 MT Radial Distance (km)
Grassland community		
1% casualties	15.8	20.8
50% casualties	8.7	11.4
Woodland community		
1% casualties	17.9	23.7
50% casualties	10.9	14.3

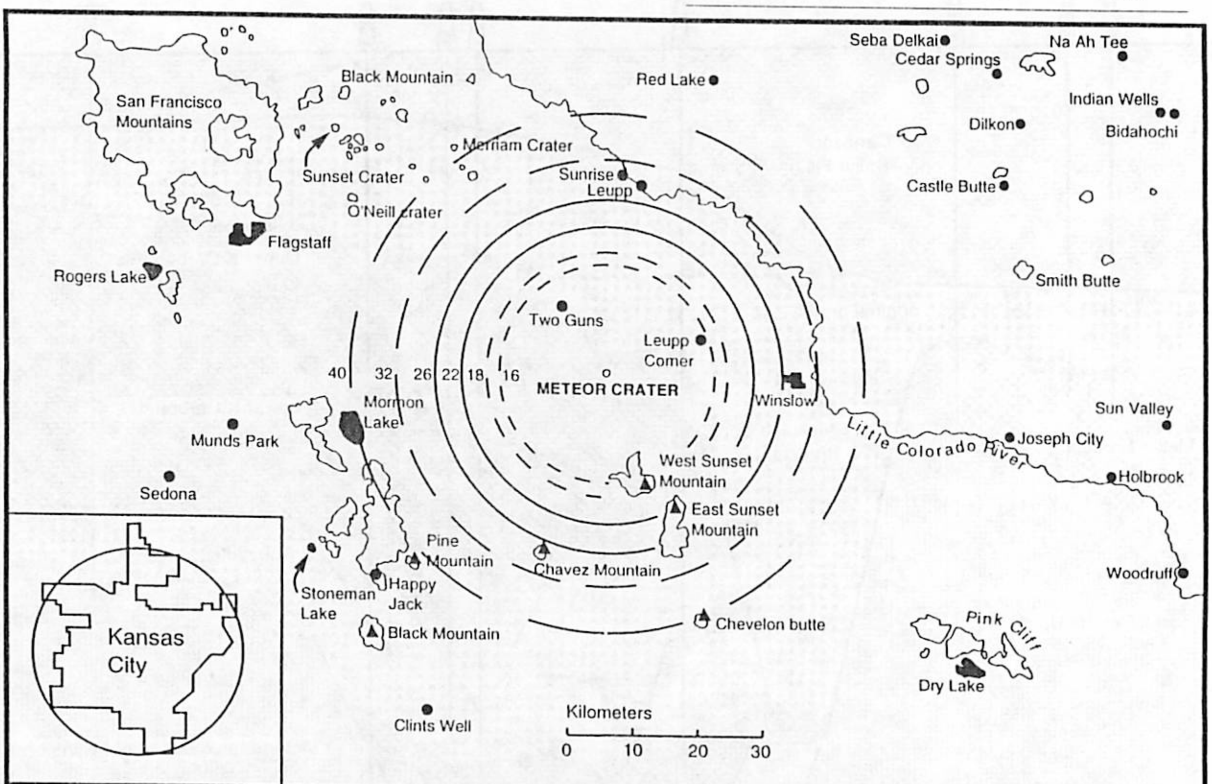


FIG. 10. Map of the Meteor Crater region, illustrating the areas of severe and moderate damage to vegetation. The inner dashed circles represent the diameter of severe (32 km) and moderate (36 km) damage to a woodland assuming a 20 MT blast. The solid circles represent the diameter of severe (44 km) and moderate (52 km) damage to a woodland assuming a 40 MT blast. The outermost dashed circles represent the 64 and 80 km diameter limits of >1 psi peak overpressures for 20 and 40 MT blasts, respectively. For comparison, the area of the Kansas City metropolitan area is shown in the inset with a 40 km diameter circle for scale, corresponding roughly to the mean range of severe to moderate woodland damage calculated for 20 and 40 MT blasts.

from the crater's center. The thickness of the layer as a function of distance is shown as a figure (Kring, 1993) at the end of this handout. The upper, generally thinner layer is composed of the high energy ejecta, ejecta which rose high enough through the atmosphere to be distributed globally. Modeling results showing the local distribution of the low energy ejecta and the global distribution of the high energy ejecta are also shown as a figure (Durda et al., 1997) at the end of this handout. The modeling shows the distribution of these two layers is not strongly affected by the incoming angle of the impactor.

Our site in Baja is about 3500 km from Chicxulub crater, so at this location we would expect to see both the low energy and the high energy layers at the K/T boundary. The expected thickness of the layers can be gotten off the previously mentioned figure from Kring (1993) and would be around 2 cm (with some large error bars on that number). So, if we could/do find the K/T boundary we would expect a thin layer over a thicker layer on the order of 2 cm thick.

Now, if we took this boundary home, and examined it in the lab, these are the sorts of things we could find:

The Iridium Anomaly

The high concentration peak of Ir at the K/T boundary was the first discovered evidence of an impact event. This peak is shown for a site in Italy as a figure at the end of this handout (Alvarez, 1987).

Why does a high peak of Ir indicate an impact event? During Earth's differentiation, siderophile elements (like Ir) would have been carried down to the core, and consequently, these elements are very rare in the crust today. However, in a relatively primitive impacting body, these elements would not be depleted. If such a body hit the Earth, it would deliver this peak of Ir. At the K/T boundary, the Ir/Au, Ir/Os, Ir/Pt, and Ir/Pd ratios are within a factor of 2 of these same ratios observed in meteorites.

Shocked Quartz

For some, shocked quartz is "the principal diagnostic criteria for identifying impact events" (Kring, 1993). There are currently only two types of events that have been found to produce shocked quartz: impact events and nuclear explosions. Shocked quartz has been found in the K/T boundary layer at sites all over the globe (Bohor et al., 1987).

A set of three photos of quartz is shown at the end of this handout (Kring et al., 1994). The first two are shocked quartz and the bottom is unshocked. As shown by this photo, the shocked quartz typically has a set of planar shock features. The planar features can be actual fractures, which are unfilled and widely spaced. The planar features can also be more closely spaced and filled with silica glass; such features are called lamellae. Either feature, though it is planar, is not an indication of the shock direction but rather a result of the crystal structure. By noting which crystal axis corresponds with the planar shock features, rough constraints can be placed on the energy associated with the shock since different crystal axes have different strengths.

Impact Melt Spherules

For a large impact, the Earth's crust can melt, and molten droplets may be ejected from the crater. These molten droplets rain out as what we call tektites or impact melt spherules. Impact melt spherules can comprise a significant portion of the low energy ejecta at some sites near Chicxulub crater. A photo of such spherules recovered from a site in Haiti is shown at the end of this handout (Kring, 1993). As can be seen in the photo, the spherules are roughly 1 mm in diameter and generally have characteristic spherical and elliptical shapes. Similar forms are observed at strewn fields.

Soot

Boundary clays from 5 sites in Europe and New Zealand show 2 to 4 orders of magnitude enrichment in elemental C (Wolbach et al., 1988). The high concentration of elemental C is mainly in the form of soot, which only forms in flames and has a characteristic "grape bunch" morphology. The other form of elemental C is irregularly shaped, platey, or pitted coarse carbon and is presumed to be charcoal which can form at lower temperatures. This increase in elemental C and soot coincides with the Ir peak.

The fact that the soot is correlated with the Ir peak and not on top of the Ir peak suggests that significant fires were ranging even as the Ir peak was being deposited. This is soon after the impact and earlier than some think fires would have started since living trees do not burn well. The global amount of C represented at the K/T boundary is very large and would correspond to about 10% of the present known biomass C. In present-day fires, soot yields are only about 1% of the total consumed C.

Amino Acids

At a site in Denmark which has a high Ir concentration, two amino acids have been reported: α-amino-isobutyric acid (AIB) and racemic isovaline (ISOVAL) (Zhao and Bada, 1989). Both of these amino acids are very rare on Earth but major amino acids in carbonaceous chondrites. The amino acids were found within 1 meter of the Ir anomaly/ boundary clay. However, the amino acids weren't detected in the boundary clay itself. The table below summarizes their data (all in ng/g).

Location	Ir	AIB	ISOVAL
+2.7 m	0.01	<0.2	<0.2
+1.2 m	0.01	<0.2	<0.2
+0.3 m	0.4	200	50
K/T	87	<0.2	<0.2
-0.5 m	0.03	350	120
-1.0 m	0.03	37	20
-2.2 m	0.03	<1	<1
-2.6 m	0.03	<0.2	<0.2

Zhao and Bada state that maybe the amino acids diffused out of the boundary clay. Others wonder how amino acids could survive the impact at all and postulate that perhaps the Earth swept up comet dust before and after the impact to explain the strange distribution of amino acids at the boundary. The AIB/ISOVAL ratio at the boundary agrees with the observed ratio in Murchison, however, the inferred AIB/Ir value at the boundary is about 100, compared to a value of 20 for Murchison. Most likely, the impactor would have had even a higher AIB/Ir ratio than this since at least a portion of the amino acids would have been destroyed during the impact.

Extinction Evidence?

The fossil record suggests there were numerous extinctions 65 million years ago, an age that correlates with the K/T boundary layer. However, does the boundary layer itself show any such evidence? A figure (Alvarez, 1987) at the end of this handout shows the same Ir anomaly at a site in New Mexico. On the right side of the figure, the measured pollen/spore ratio is plotted as a function of the same stratigraphic depth as the Ir abundance. Within a cm of the same location as the Ir peak, the pollen/spore ratio shows an equally sharp drop. At this site in New Mexico, 1 cm is believed to correspond to about 140 years. This data suggests plant life felt the effects of the K/T event.

References:

Alvarez, L. W. (1987) Mass extinctions caused by large bolide impacts, Physics Today, 24-33.

Bohor, B. F. et al. (1987) Shocked quartz in the Cretaceous-Tertiary boundary clays: evidence for global distribution, Science 236, 705-709.

Durda, D. D. et al. (1997) Model calculations of the proximal and globally distributed distal ejecta from the Chicxulub impact crater, LPSC XXVIII, 315-316.

Gastil, Phillips, and Allison (1971). Reconnaissance Geologic Map of the State of Baja California, Universidad Autonoma de Baja California and San Deigo State Univ., GSA memoir 140.

Hildebrand et al. (1991), The Chicxulub Crater: A possible Cretaceous-Tertiary boundary impact crater on the Yucatan Peninusla, Mexico. Geology, 19:867-871.

Kring, D.A. (1993), The Chicxulub Impact Event and Possible Causes of K/T Boundary Extinctions, in Proceedings of the First Annual Symposium of Fossils of Arizona, D. Boaz and M. Dornan (eds.) Mesa Southwest Museum and Southwest Paleontological Society, Mesa (Arizona), 63-79.

Kring, D. A. et al. (1994) Provenance of mineral phases in the Cretaceous-Tertiary boundary sediments exposed on the southern peninsula of Haiti, EPSL 128, 629-641.

Ocampo, Pope and Fischer (1996), Ejecta blanket deposits of the Chicxulub crater from Albion Island, Belize. GSA Special Paper 307.

Pierazzo, Elisabetta (1997), The Chicxulub impact event and the environmental catastrophe at the end of the Cretaceous period. PhD Dissertation, Univ. of AZ.

Sharpton et al. (1996), A model of the Chicxulub impact basin based on evaluation of geophysical data, well logs, and drill core samples. GSA Special Paper 307.

Wolbach, W. S. et al. (1988) Global fire at the Cretaceous-Tertiary boundary, Nature 334, 665-669.

Zhao, M. and Bada, J. L. (1989) Extraterrestrial amino acids in Cretaceous/Tertiary boundary sediments at Stevns Klint, Denmark, Nature 339, 463-465.

Thanks to Joe Kirschvink at CALTEC, who gave us details on how to find the K/T stop and what to look for when we got there.

Thanks to Dave Kring, for a hell of a lot of personal communication and guidance.

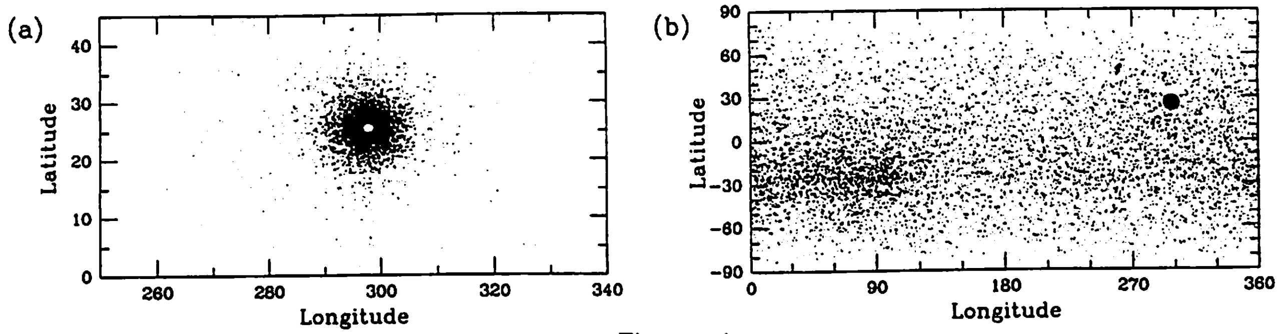


Figure 1

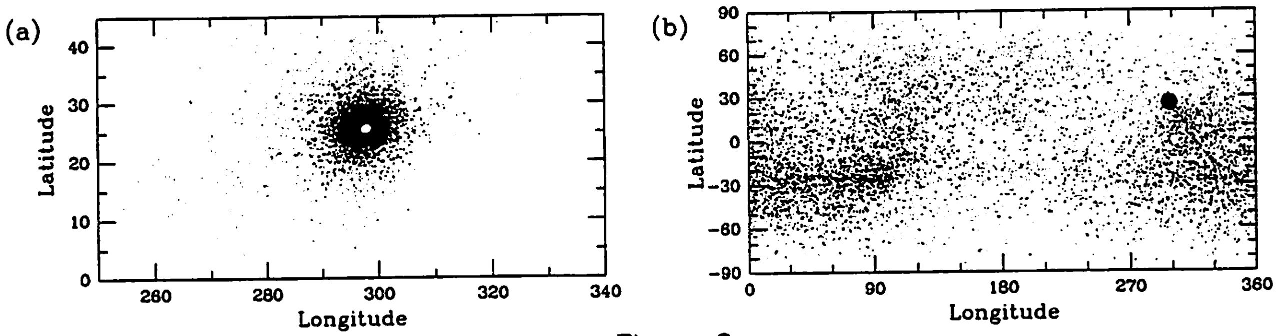


Figure 2

Figure 1. Distribution of (a) low-energy ejecta and (b) high-energy ejecta following a vertical impact at the site of Chicxulub (62.26 W, 25.56 N 65 Ma). Figure 2. Distribution of (a) low-energy ejecta and (b) high-energy ejecta following an oblique impact with a trajectory from the southeast at an angle of 25° above the surface. Most of the mass is in the low-energy ejecta, so the particle densities in (a) and (b) are not directly comparable in terms of mass. In addition, we did not attempt to simulate the instabilities in the low-energy ejecta that can produce hummocky distribution of material or rays.

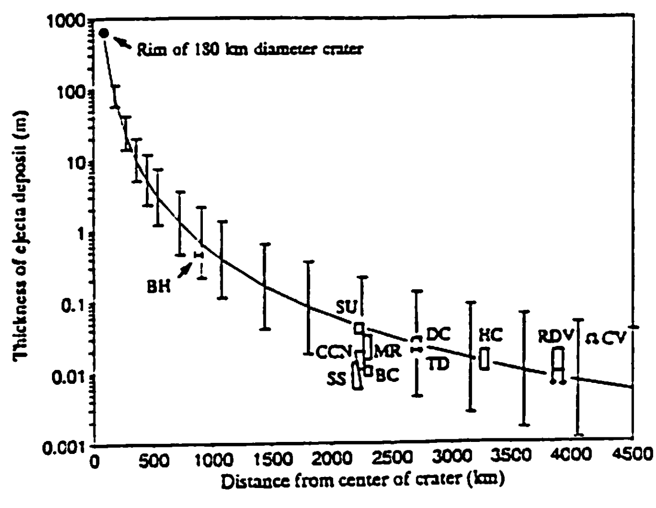
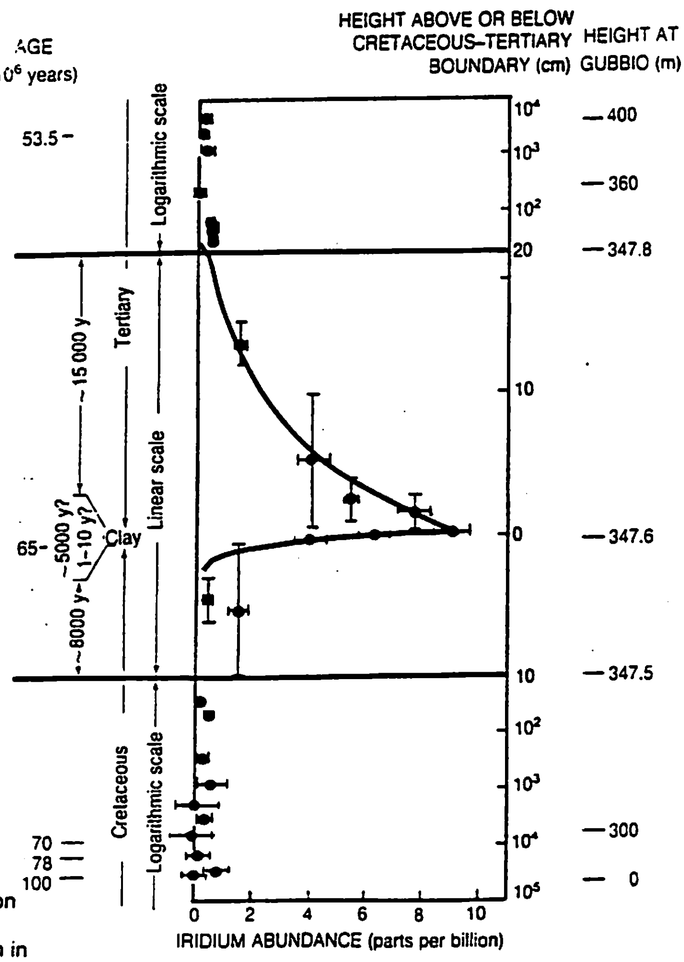


Figure 4. The thickness of ejecta at 11 K/T boundary sites as a function of distance from the Chicxulub crater. These data are consistent with the trend (curved line) calculated from scaling laws derived studies of the ejecta around other impact craters and experimental explosions (After Vickery et al. (1992), with additional unpublished data from Kring).



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Iridium concentration as a function of stratigraphic position in the geological record at Gubbio, Italy.

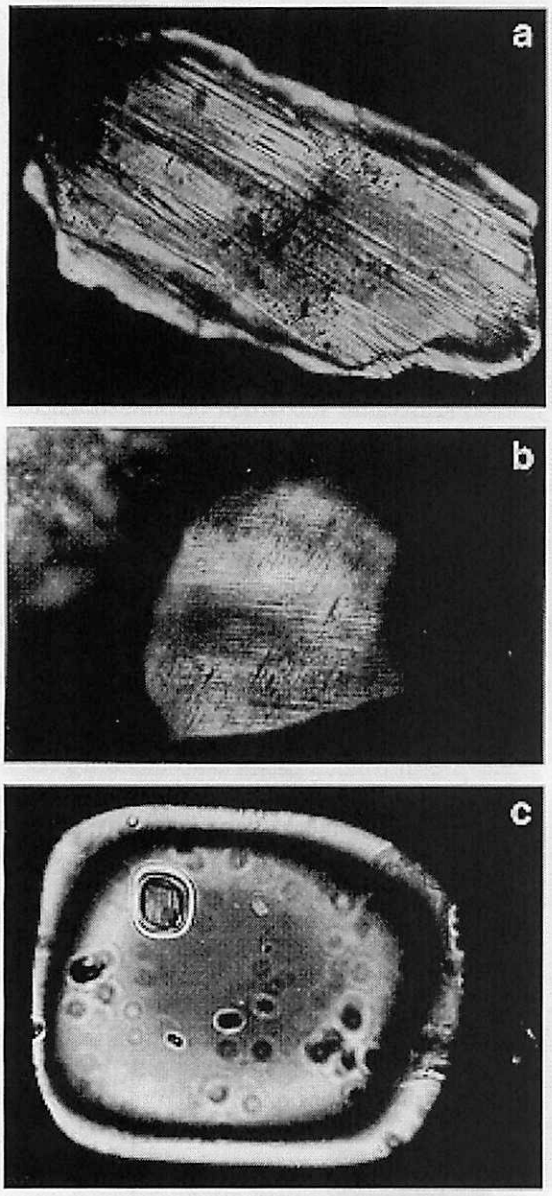


Fig. 4. Shocked quartz grains from site 1 and an unshocked quartz grain with a β form from site 4; transmitted light photographs with crossed nicols. (a) Shocked quartz grain (0.45 mm long) with two sets of lamellae visible in sample B6B. (b) Shocked quartz grain (0.24 mm long) with two sets of lamellae visible in sample B4B. (c) Unshocked β form quartz grain (0.16 mm long) in sample B0TG.

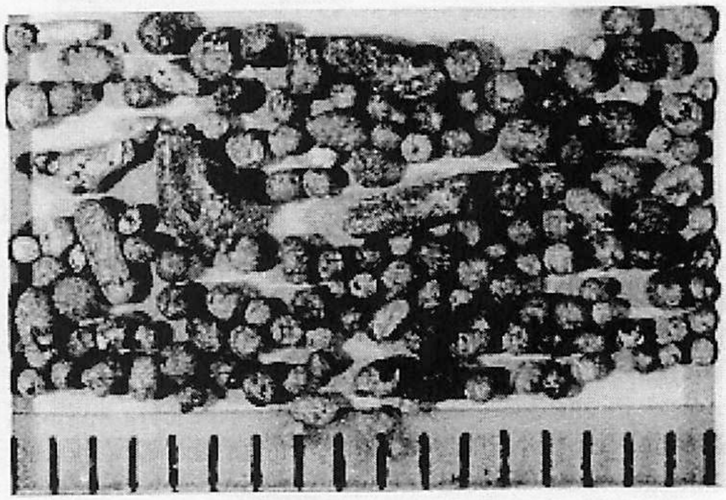
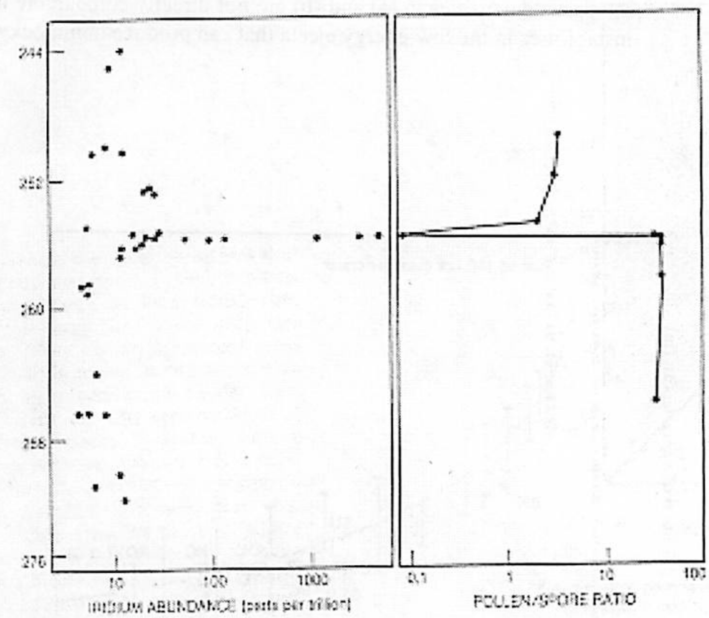


Figure 3. Altered tektites from the K/T boundary sediments near the village of Beloc, Haiti. These objects form a bed nearly half a meter thick, which is covered by a second, Ir-rich bed. The scale has 1 mm divisions.



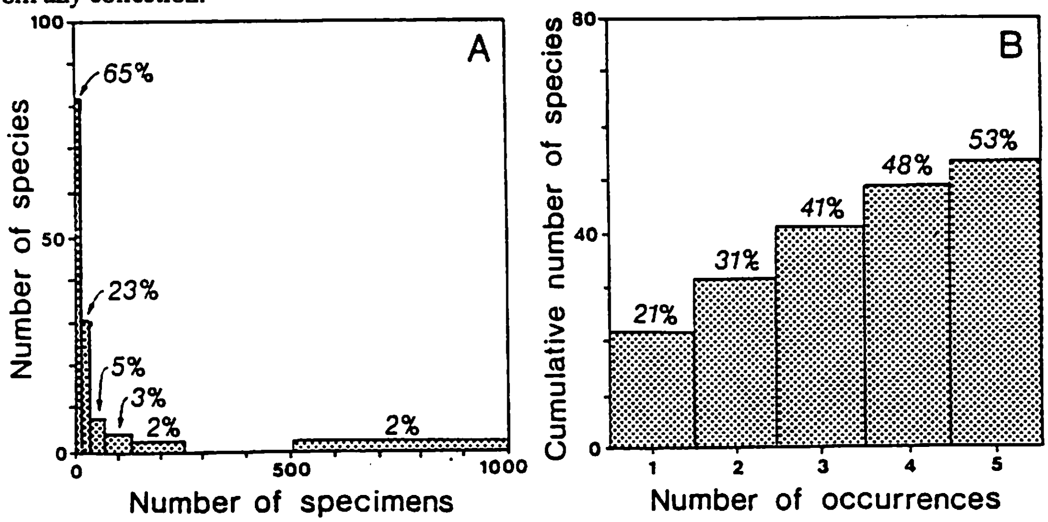
Coincidence of iridium enhancement and drop in the ratio of fossil pollen to fern spores. These data from the Raton Basin of New Mexico indicate that plants as well as animals felt the effect of a bolide impact. The drop in the ratio of angiosperm pollen to fern spores indicates a shift in the flora from Cretaceous species to Tertiary species. The extrema of the two peaks occur in the same centimeter of stratigraphic height.

Figure 5

The K/T extinctions in the Paleontologic record: debate and controversies

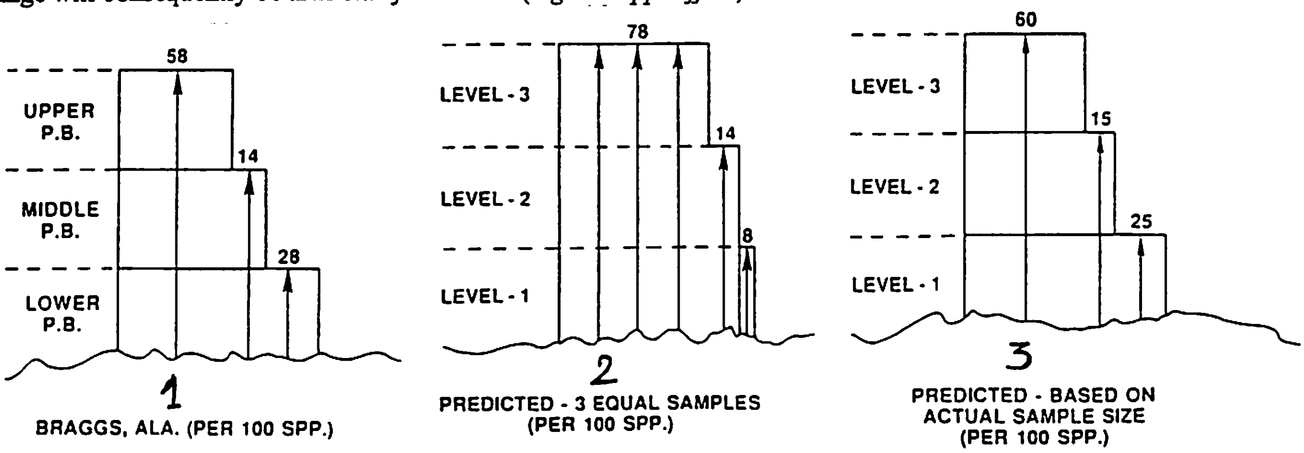
Elisabetta Pierazzo

The ultimate source of the data used to analyze mass extinctions are local outcrops and cores. The general experimental procedure is to locate fossiliferous horizons in a section, collect fossils from each horizon (or at constant intervals) and then remove the collection to the laboratory, where fossil identification, their abundances, and other analyses are conducted. In nearly every ecological setting, living and fossil, there are a few abundant species, a few more common species, and a large number of rarer species. The consequence of very uneven species abundance for paleontologic sampling is that large numbers of species actually preserved in most fossiliferous horizons will be missing from any collection.



A. Species abundance curve showing that the majority of species are represented by few specimens even in a very large collection (from *Koch*, 1978). The widths of the histogram bars increase geometrically with abundance. **B.** Cumulative histogram of occurrences of rare species among 578 collections of mid-Maastrichtian molluscs from the Atlantic and Gulf Coastal Plains of North America (data set 9 of *Koch*, 1987). More than half of the total species occur in fewer than 1% (5 of 578) of the collections.

Collections immediately below an event horizon will contain only a few of the rare species found lower in any stratigraphic section, even if all survived up to the bio-event. The range of a taxon is usually given as extending from the first occurrence to the last occurrence, regardless of whether or not the taxon occurs at each imtermediate stratigraphic level. Because the last sample occurrence of some rarer species will occur below the bio-horizon at which the species actually disappears where taxa persist after their last known occurrence in the fossil record, the range will consequently be artificially truncated (*Signor-Lipps effect*).



1. Stepwise extinction pattern observed when the mollusc data of Bryan and Jones (1989) are plotted as species ranges toward the K/T boundary (P.B.=Prairire Bluff). **2.** Expected stepwise extinction pattern for 100 species ranging towards a sudden mass extinction event if sample sizes for the youngest three levels are equal. **3.** Expected stepwise extinction pattern for 100 species ranges towards a sudden mass extintion event if the sample sizes for the youngest three levels are the same as those used for the data of Bryan and Jones (1989).

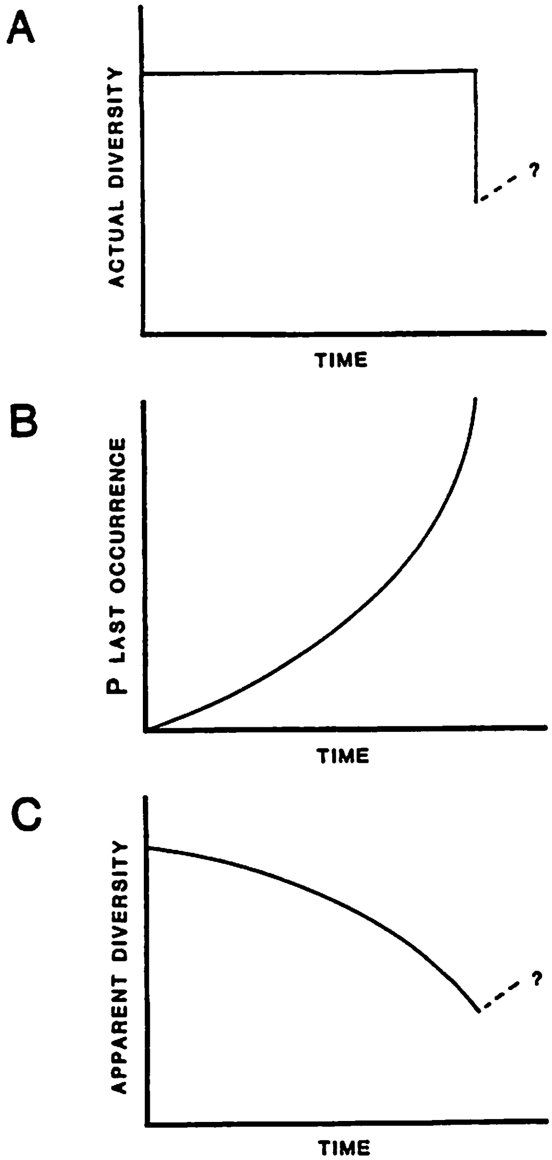


Fig. 2. Alteration of diversity patterns by artificial range truncation. In Fig. 2a we illustrate a hypothetical diversity curve, where diversity is suddenly reduced by a catastrophic extinction event. Fig. 2b presents a cumulative probability curve, showing the likelihood of different amounts of artificial range truncation. Imposing the artificial range truncation suggested in Fig. 2b on the hypothetical diversity pattern (Fig. 2a) would produce an apparent gradual decline in diversity, as shown in Fig. 2c.

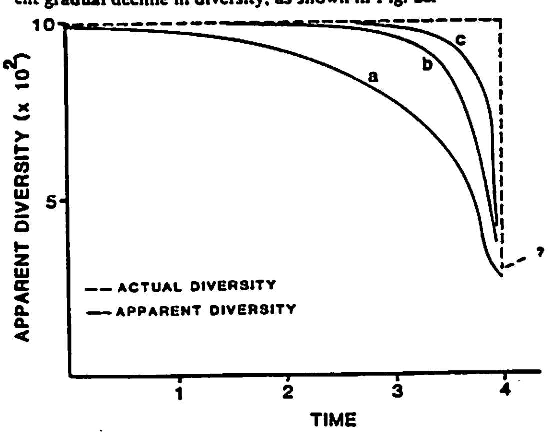


Fig. 3. Effects of improved sampling on artificial range truncation. If sampling was consistent but not thorough in each of four hypothetical time intervals the apparent diversity could appear as illustrated by curve a, despite the constant diversity in all four time intervals followed by a catastrophic extinction after time 4. Improved sampling, illustrated by curves b (twice the sampling hypothesized by curve a) and c (three times the sampling of a) improves the match between apparent and "actual" diversity. Different sedimentary sections must be assessed in a similar way. We expect nearshore marine and terrestrial sections to be farther from actual diversity (a or b) than the deep sea plankton record (c), for example.

Signor-Lipps Effect

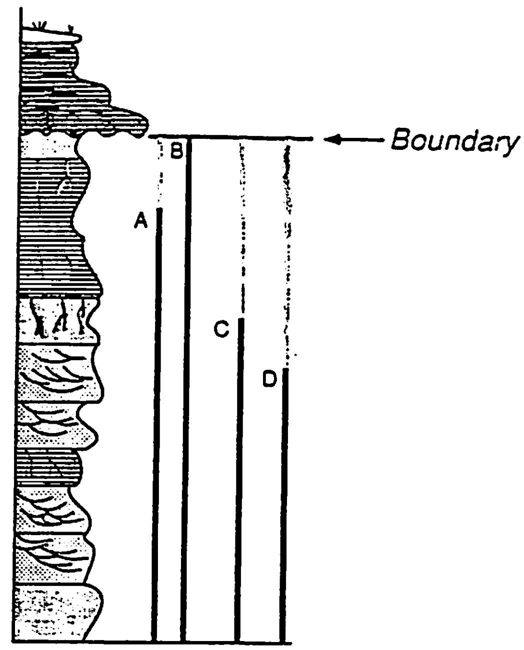


Figure 16.3 **Range extensions. Because of the Signor-Lipps effect, biostratigraphers commonly extend the ranges of taxa to the nearest boundary. In this hypothetical case, the solid black lines represent the actual ranges of lineages A, B, C, and D. Only B goes to the boundary. The actual ranges of A, C, and D fall short of the boundary, but would be extended by biostratigraphers to the boundary (represented by the gray lines). Such extensions make the extinction appear catastrophic, even if it is not.**

G. Keller et al., Palaeogeography, Palaeoclimatology, Palaeoecology 119 (1995) 221–254

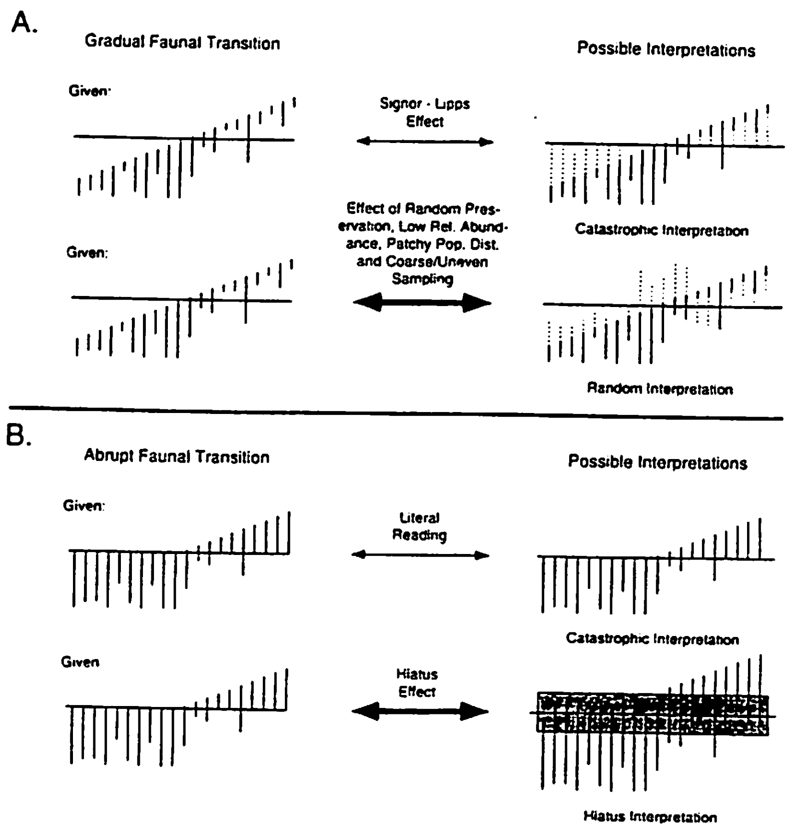
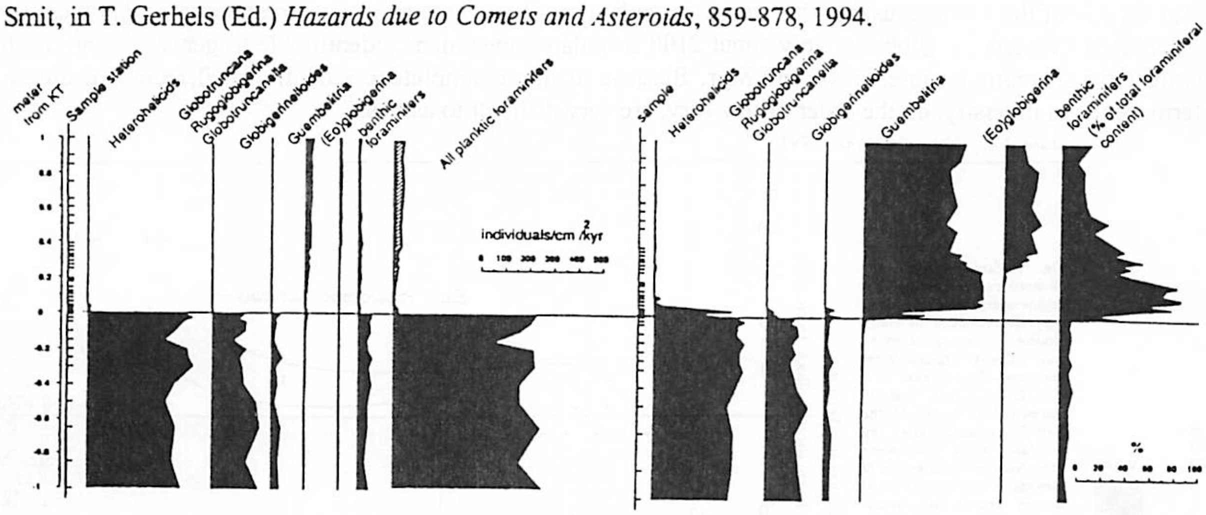


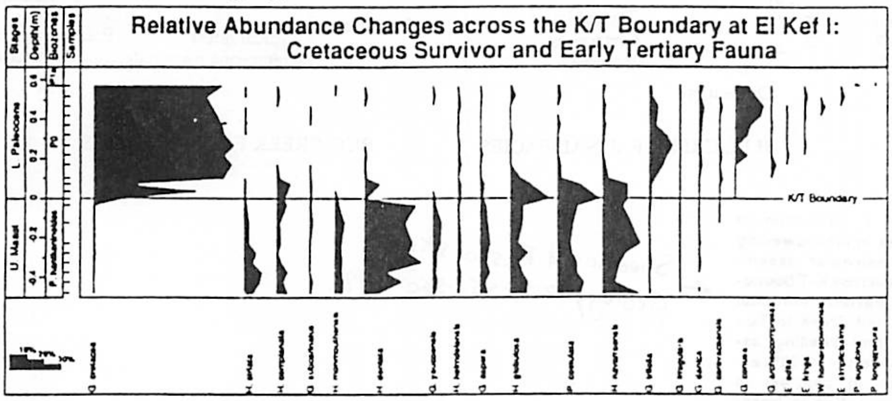
Fig. 16. Possible interpretations of gradual (A) and abrupt (B) faunal turnover patterns. See text for discussion.

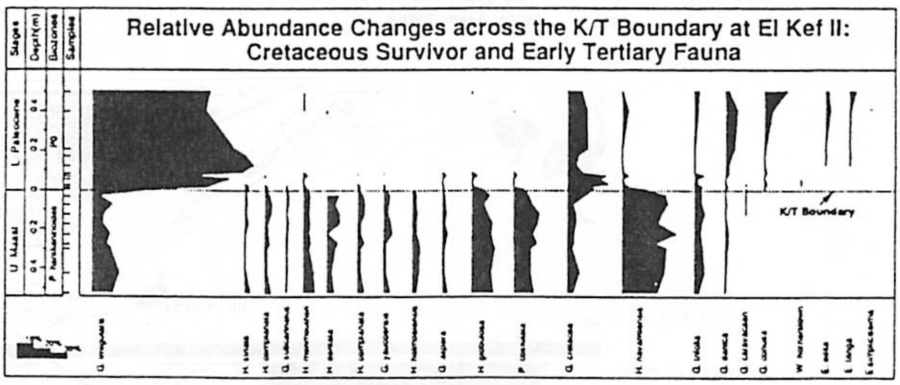
The controversy between sudden and synchronous vs. gradual or stepped extinction.

Smit, in T. Gerhels (Ed.) *Hazards due to Comets and Asteroids*, 859-878, 1994.



Keller et al., *Palaeogeog., Palaeoclimatol., Palaeoecol. 119*, 221-254, 1995



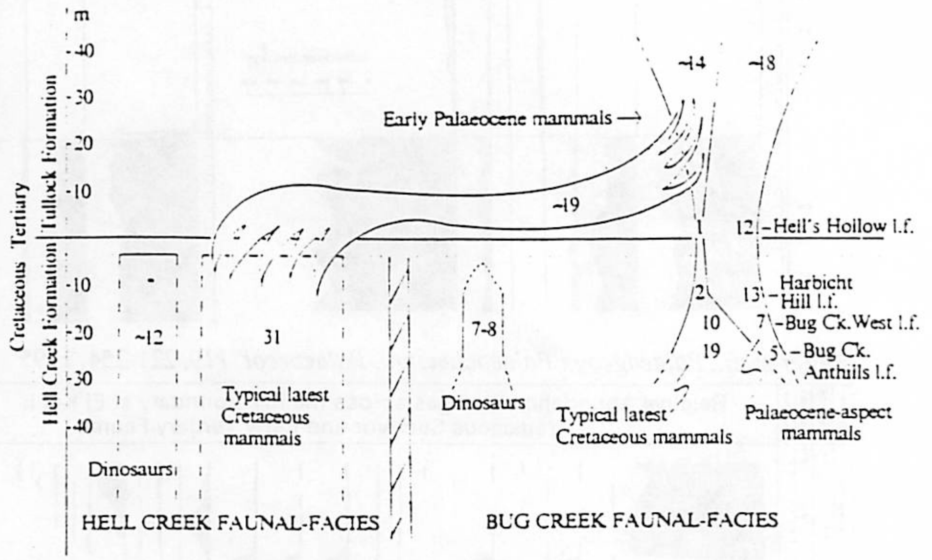


Blind tests. An effort to settle the debate between sudden and gradual extinction in the marine realm was carried out few years ago. A series of blind tests were performed by four micropaleontologists (X. Orue-extebarria, Univ. Pais Vasco; R.K. Olsson, Rutgers Univ.; B. Masters, Sapolpa, Oklahoma; J.I. Canudo, Univ. Zaragoza) on six (coded) samples from the El Kef section, Tunisia. The results of the blind tests werer presented at the Snowbird III conference (1994), in Houston, TX, by they did not seem to settle the arguments as hoped. Keller et al. (1995) maintains that the fact that each analysis shows disappearances before and after the K/T boundary, in agreement with her work, is an indication of a gradual, or stepped, extinction. However, according to Smit (*Nature 368*, 809-810, 1994), because of the Signor-Lipps effect, each individual analysis show disappearance of (rare) species both before and after the K/T, but when lumped together they do not demonstrate any real disappearance before the K/T boundary. Indeed, all the seven species that Keller et al. (1995) claim to disappear before the boundary are found by one or another of the blind tests investigators closer to the boundary.

Vertebrate extinctions. The terrestrial vertebrate fossil record across the K/T boundary is far less complete than that of marine microfossils. Dinosaurs are undoubltedly the most spectacular of the various living beings that become extinct at the end of the Cretaceous, but they represent only a small percentage of vertebreate species that were extant during the latest Cretaceous. Globally, only aobut 2100 articulated specimens indentifiable to genus of dinosaur have been collected , spanning an interval of 160 Myr. Because of the incompleteness of the fossil record of dinosaurs, short term trends in diversity, on the order of few Mry, are very difficult to assess.

Nature Vol. 291 25 June 1981

Fig. 1 Stratigraphical and biostratigraphical sequence in northeastern Montana showing relationships of the Hell's Hollow l.f. (local fauna) to the Bug Creek faunal-facies sequence—Bug Creek Anthills l.f., Bug Creek West l.f., Harbicht Hill l.f. (ref. 5), the Hell Creek faunal-facies and the later early Palaeocene sites. Numbers and widths of bars approximate numbers of species known at various levels. Numbers for Bug Creek faunal-facies dinosaurs are from ref. 6, numbers for the highest early Palaeocene mammals from refs 5 and 9, and the remainder from ref. 3.



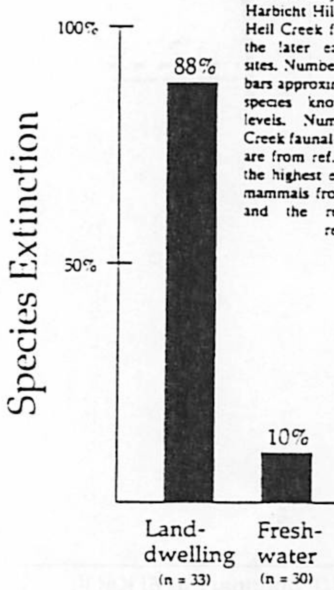
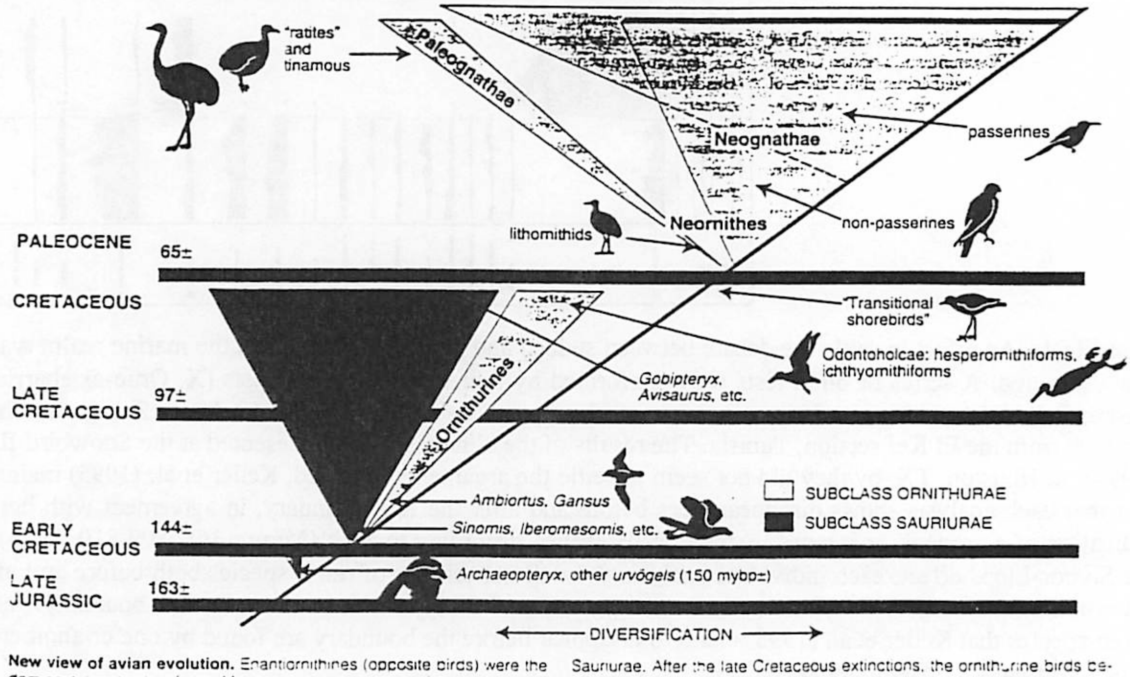


Figure 1. Extinction of species in land-dwelling and freshwater assemblages across K-T boundary in eastern Montana. From Hell Creek to Tullock, land-dwelling assemblage shows 88% extinction in contrast to 10% extinction in freshwater assemblage.

← Sheehan & Fastovsky Geology 20, 556-560, 1992



New view of avian evolution. Enantiornithines (opposite birds) were the dominant landbirds of the Mesozoic but coexisted with modern-type ornithurine birds in the early Cretaceous. *Archaeopteryx* may be closely allied with the enantiornithines, and together, they constitute the subclass Sauriurae. After the late Cretaceous extinctions, the ornithurine birds began a modern, explosive adaptive radiation, almost all orders appearing within a period of 10 or so million years. By the Miocene, passerines became the predominant landbirds. Silhouettes not to scale.

Dinosaur Extinction

Sloan et al., *Science 232*, 629-633, 1986

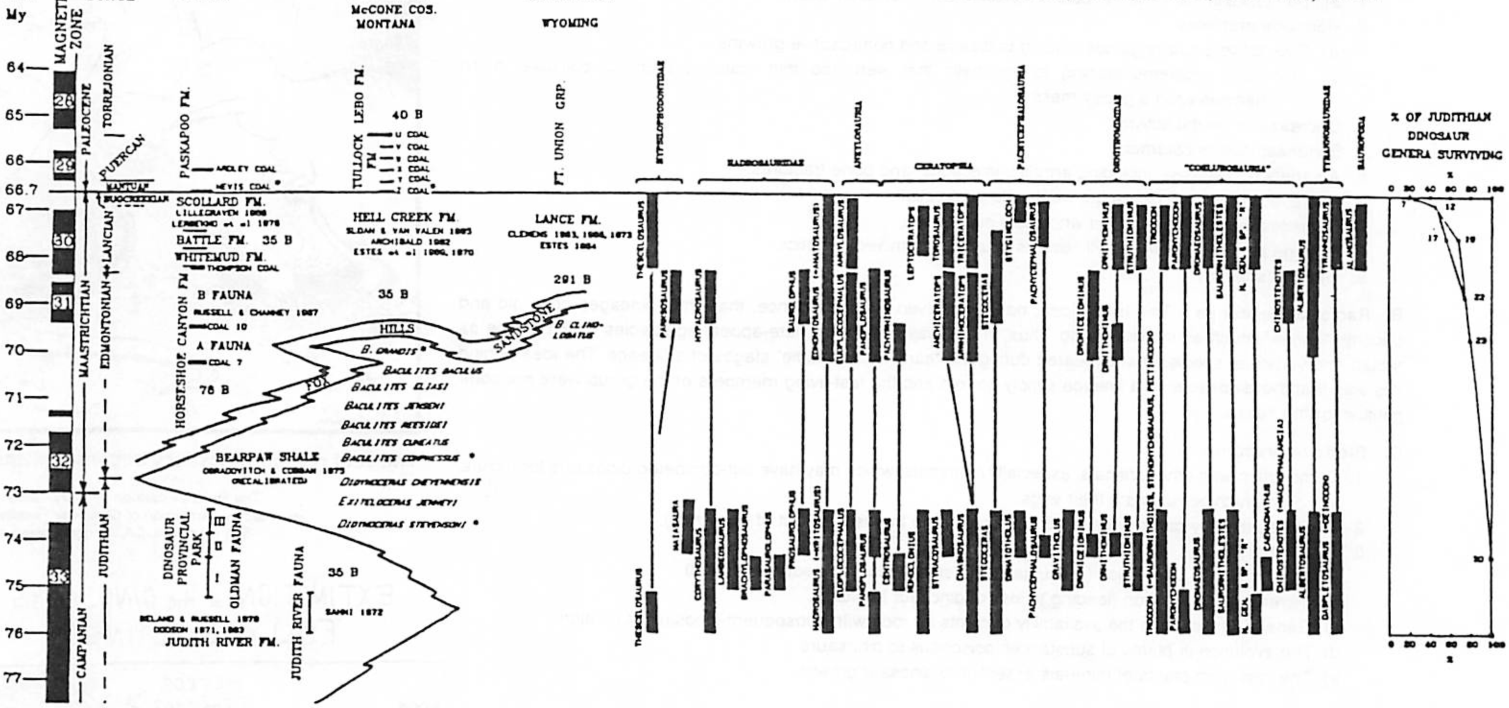


Fig. 1. Ages, phyletic relations, and stratigraphic occurrence of Late Cretaceous dinosaurs in Alberta, Montana, and Wyoming. The left portion of the diagram shows the stratigraphic occurrence of the dinosaur faunas, their relation to the adjacent ammonite zones of the Bearpaw Shale and the overlying Paleocene rocks, a time scale, and a magnetochron scale. The asterisk indicates a radioactive date. Solid bars indicate presence of agenus of dinosaur, and narrow connecting lines the inferred presence or ancestry. Right-hand graph shows percent of Judithian dinosaurs surviving. Sedimentation rater are in Benioff (B) units.

Table 2. Number of dinosaur specimens per square kilometer of outcrop per 9 m interval of stratigraphic section (exclusive of washing localities.

Stratigraphic interval below Z coal (m)	Number of dinosaur skeletons or large bones	Area prospected (km^2/ 9 m)	Dinosaurs per square kilometer
0–9	6	4.18	1.44*
10–18	13	4.18	3.1
19–27	9	3.93	2.29
28–36	14	2.76	5.07
37–45	4	2.31	1.73
46–54	6	2.42	2.48

*The prospecting success in the highest level differs significantly [χ^2 test; $P < 0.05$] from the combined others, holding the observed areas and total number of specimens constant. The highest level was thought from other evidence (3) to show a decline in dinosaur abundance.

Sheehan et al., in *The Cretaceous-Tertiary Event and other Catastrophes in Earth History*, 477-489, 1996

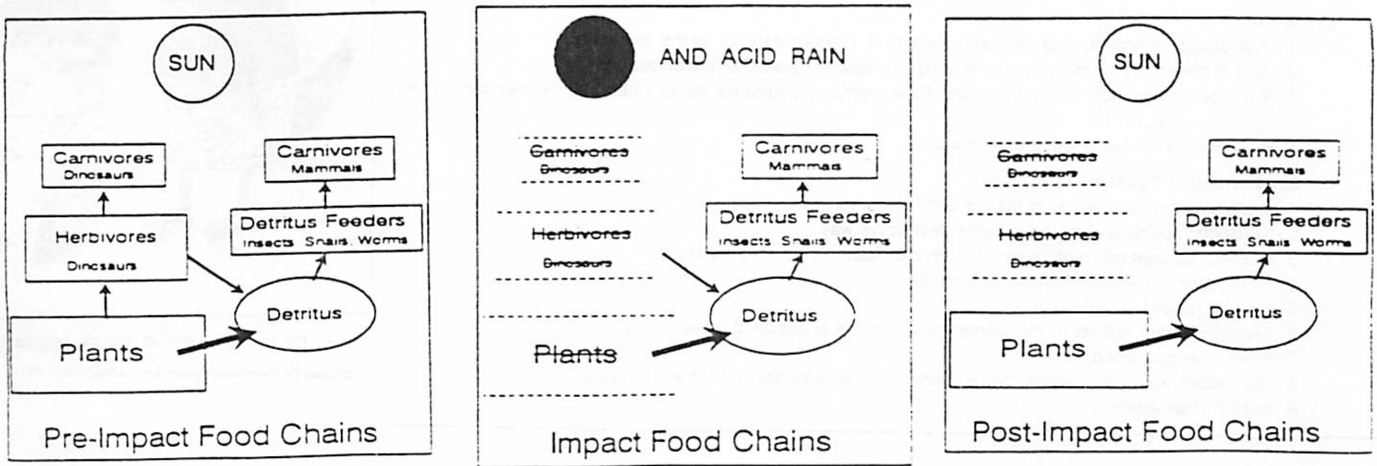


TABLE 17.1 PROPOSED CAUSES FOR THE EXTINCTION OF THE DINOSAURS

(after Benton, 1990)

I. PROPOSED BIOTIC CAUSES

A. Medical Problems

1. Slipped disks in the vertebral column causing dinosaur debilitation.
2. Hormone problems.
   a) Overactive pituitary glands leading to bizarre and nonadaptive growths.
   b) Hormonal problems leading to eggshells that were too thin, causing them to collapse in on themselves in a gooey mess.
3. Decrease in sexual activity.
4. Blindness due to cataracts.
5. A variety of diseases, including arthritis, infections, and bone fractures.
6. Epidemics leaving no trace but wholesale destruction.
7. Parasites leaving no trace but wholesale destruction.
8. Change in ratio of DNA to cell nucleus causing scrambled genetics.
9. General stupidity.

B. Racial Senescence – This is the idea, no longer given much credence, that entire lineages grow old and become "senile," much as individuals do. Thus, in this way of thinking, late-appearing species would not be as robust and viable as species that appeared during the "early" and "middle" stages of a lineage. The idea behind this was that the dinosaurs as a lineage simply got old and the last-living members of the group were not competitive for this reason.

C. Biotic Interactions

1. Competition with other animals, especially mammals, which may have out-competed dinosaurs for niches, or which perhaps ate their eggs.
2. Overpredation by carnosaurs (who presumably ate themselves out of existence).
3. Floral changes.
   a) Loss of marsh vegetation (presumably the single important source of food).
   b) Increase in forestation (leading to loss of dinosaur habitats).
   c) General decrease in the availability of plants for food with subsequent dinosaur starvation.
   d) The evolution in plants of substances poisonous to dinosaurs.
   e) The loss from plants of minerals essential to dinosaur growth.

II. PROPOSED PHYSICAL CAUSES

A. Atmospheric Causes

1. Climate becoming too hot, so they fried.
2. Climate becoming too cold, so they froze.
3. Climate becoming too wet, so they got waterlogged.
4. Climate becoming too dry, so they desiccated.
5. Excessive amounts of oxygen in the atmosphere causing
   a) Changes in atmospheric pressure and/or atmospheric composition that proved fatal; or
   b) Global wildfires that burned up the dinosaurs.
6. Decrease in the amount of oxygen in the atmosphere affecting the breathing capabilities of dinosaurs
7. Low levels of CO_2 removing the "breathing stimulus" of endothermic dinosaurs.
8. High levels of CO_2 asphyxiating dinosaur embryos.
9. Volcanic emissions (dust, CO_2, rare-earth elements) poisoning dinosaurs one way or another.

B. Oceanic and Orographic Causes

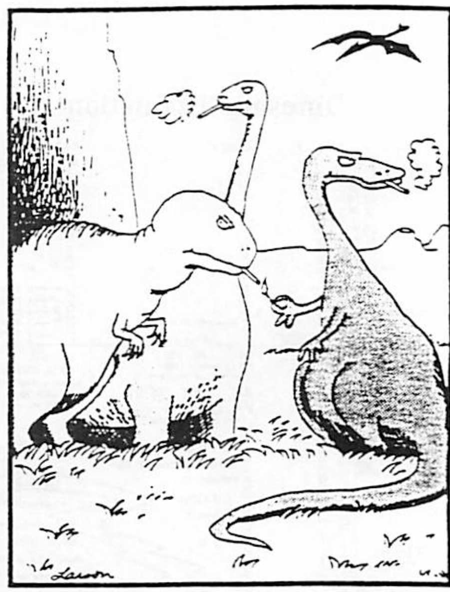
1. Marine regression producing loss of habitats.
2. Draining of swamp and lake habitats.
3. Stagnant oceans producing untenable conditions on land.
4. Spillover into the world's oceans of Arctic waters that had formerly been restricted to polar regions, and subsequent climatic cooling.
5. The opening of Antarctica and South America, causing cool waters to enter the world's oceans from the south, modifying world climates.
6. Reduced topographic relief and loss of habitats.

C. Other

1. Fluctuations in gravitational constants leading to indeterminate ills for the dinosaurs.
2. Shift in the earth's rotational poles leading to indeterminate ills for the dinosaurs.
3. Extraction of the moon from the Pacific Basin perturbing dinosaur life as it had been known for 160 million years(!).
4. Poisoning by uranium from the earth's soils.

D. Extraterrestrial Causes

1. Increasing entropy leading to loss of large life forms.
2. Sunspots modifying climates in some destructive way.
3. Cosmic radiation and high levels of ultraviolet radiation causing mutations.
4. Destruction of the ozone layer, causing (3).
5. Ionizing radiation as in (3).
6. Electromagnetic radiation and cosmic rays from the explosion of a supernova.
7. Interstellar dust cloud.
8. Oscillations about the galactic plane leading to indeterminate ills for the dinosaurs.
9. Impact of an asteroid.


The real reason dinosaurs became extinct

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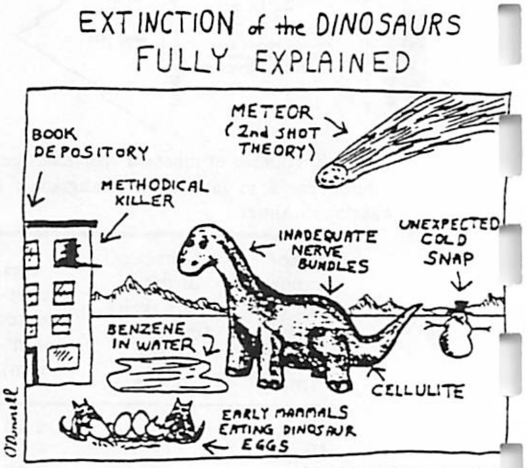

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The real reason dinosaurs are extinct

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Our Nemesis

Eric Wegryn

Geology and biology are intimately linked through natural history. The same strata that contain the record of the geologic development of our planet also contain fossils which reveal the course of evolution of life on Earth. Many of the boundaries in the geologic calendar correspond to significant changes in the fossil record, as contained in the geologic strata. The obvious question is, What determines these boundaries?

In a now famous 1980 paper, Luis and Walter Alvarez[1] advanced the theory that the mass extinction event separating the Cretaceous period from the Tertiary was caused by a large body impacting on Earth and severely altering the climate. This led to one of the largest dyings in the history of life on Earth, which was then followed by the flourishing of previously minor species of plants and animals (most notably the mammals).

But this event (whatever its cause) is only the most recent case of such a major extinction. The fossil record reveals many such occurrences of relatively sudden mass dyings, to a greater or lesser extent.

In 1984 David Raup and John Sepkoski[2] reported finding a strong periodicity in the extinction record from the end of the Permian period to the end of the Cretaceous (covering about 250 million years). They cited 12 large extinction events, 10 of which correspond very well with a 26 million year period.

802 Evolution: Raup and Sepkoski

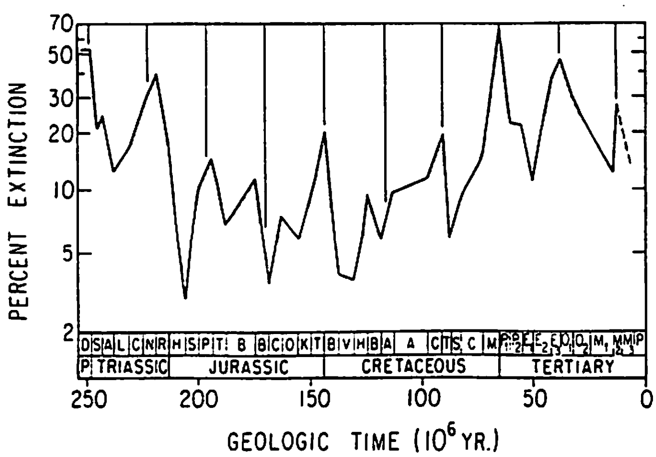


FIG. 1. Extinction record for the past 250 ma. Letter codes (bottom) identify stratigraphic stages. The best-fit 26-ma cycle is shown along the top. The relative heights of extinction peaks should not be taken as literal expressions of extinction intensity because the absence of extant taxa exaggerates the heights of younger peaks.

Marc Davis, Piet Hut, and Richard Muller[3], inspired by the Alvarez's theory that the K/T extinction was caused by a large impact event, quickly suggested that the periodicity of extinctions could be explained if there were some astronomical phenomenon which could significantly increase the number of potential impactors reaching Earth with a 26 million year period. They postulated a small dark companion to our Sun, which they dubbed *Nemesis*., (Steven Jay Gould[4] suggested it be called *Siva*) which could conceivably perturb cometary bodies in the Oort cloud to fall in great numbers into the inner solar system, showering the planets.

Other studies have shown evidence of a similar periodicity (~28 million years) in the cratering record on Earth (and on the Moon?). However, conclusions based upon crater counts are always vulnerable to the assumptions that were made about the cratering rate as a function of time, and the inferred period must be viewed with a skeptical mind.

There are other difficulties too, of course. Raup and Sepkoski were criticized for their method of calculating extinctions, which included counting extinctions only at the taxonomic family level (extinction of a family implies the extinction of every species in it, and is thus much more severe), and disregarding all currently existing species, to enhance the signal of extinctions in the fossil record. Many other scientists have taken the position that the signal of extinctions in the fossil record is very weak, and cannot easily be separated from the noise of the background extinction rate.

Raup points out however that the mass extinction events "cut across functional, physiological, and ecological lines . . . In other words, extinction is physically rather than biologically driven."[5] If the periodicity is real, then some physical process with a period of tens of millions of years needs to be forwarded to account for it. Although there are some geologic, geochemical,[5] and climatic phenomenon with time scales of this magnitude (e.g. tectonic plate movements and Milankovitch cycles), astronomical phenomenon are more likely contenders for causing the extinction of large numbers of species. Theories invoking the passage of the solar system through the plane of the galaxy (its epicyclic motion) or through the spiral arms have been advanced, but do not seem to provide answers any more convincing than the Nemesis theory.

However, a fairly thorough search for a solar companion has been conducted, and has not yielded any positive results. An object orbiting the Sun with a period of 26 million years would have a semimajor axis of about 88,000 A.U., or 1.4 light years. If one existed, it should have shown up in infrared surveys.

So is there really a periodicity in mass extinctions, and if so, what is the cause? The answer does not seem to be convincing either way.

In their 1984 paper, Davis, Hut, and Muller expressed the concern that "if the companion is not found, this paper will be *our* nemesis." Whether or not the periodicity is real, it has provoked a useful and insightful scientific investigation. But it also reminds us to beware of that all too tempting practice of geologists: wild speculation.

References:

1 L.W.Alvarez, W.Alvarez, F.Asaro, and H.V.Michel, Extraterrestrial cause for the Cretaceous-Tertiary extinction, *Science* **208**, 1980

2 D.M. Raup and J.J. Sepkoski, Periodicity of extinctions in the geologic past, *Proc. Natl. Acad. Sci.* **81**, 1984

3 M.Davis, P.Hut, and R.A.Muller, Extinction of species by periodic comet showers, *Nature* **308**, 1984

4 S.J.Gould, The Cosmic Dance of Siva, *The Flamingo's Smile*, 1985

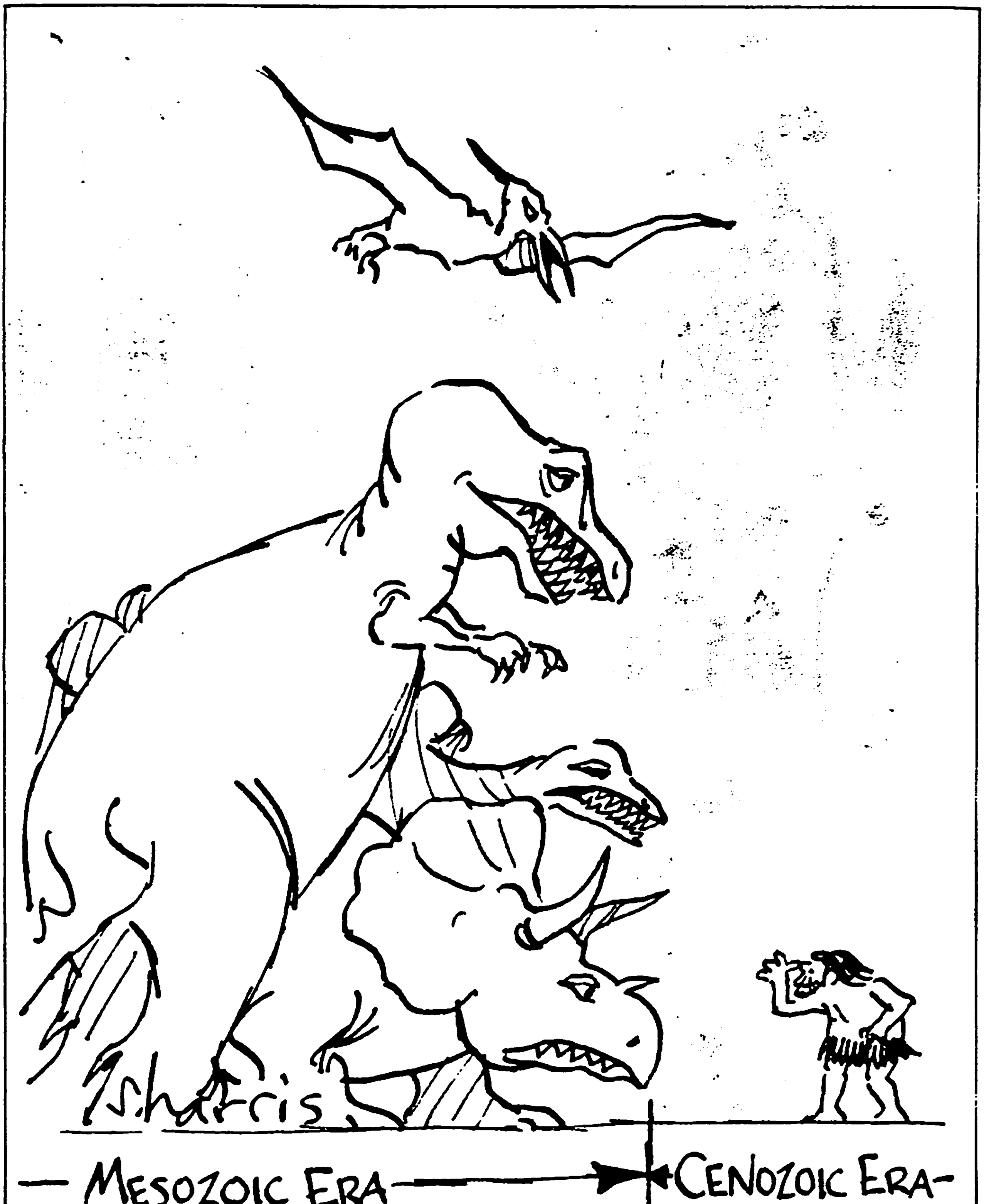
5 D.M.Raup and G.E.Boyajian, Patterns of generic extinction, *Paleobiology*, **14**, 1988

6 C.Patterson and A.B.Smith, Periodicity in extinction: the role of systematics, *Ecology*, **70**, 1989

7 C.Moses, A geochemical perspective on the causes and periodicity of mass extinctions, *Ecology*, **70**, 1989

8 P.R.Weissman, Are periodic bombardments real?, *Sky and Telescope*, March 1990

9 M.Rampino, Mass extinctions and periodicity, *Science*, 1995


S.Harris
MESOZOIC ERA
CENOZOIC ERA

Algal Mats, Stromatolites, and Microbial Scum: Microbial Lifestyles of the Rich and Slimy

barb cohen and david trilling

------------------------What is an **algal mat?**----------------------

A layered community of microbes (prokaryotes and eukaryotes) which survives interdependently. Algal mats are typically found in extreme environments where the "grazing stress" is small. Algal mats are **BIOLOGICAL ENTITIES.**

Intertidal flats are common places to find algal mats. Cyanobacteria are the principle microorganisms involved.

Algal mats are typically centimeters thick, but can grow to half a meter!

The microbes have to be in water to survive -- but not water that's too deep! Hence, an evaporite flat, where the water level changes by only a few centimeters in each tidal cycle, is a good environment.

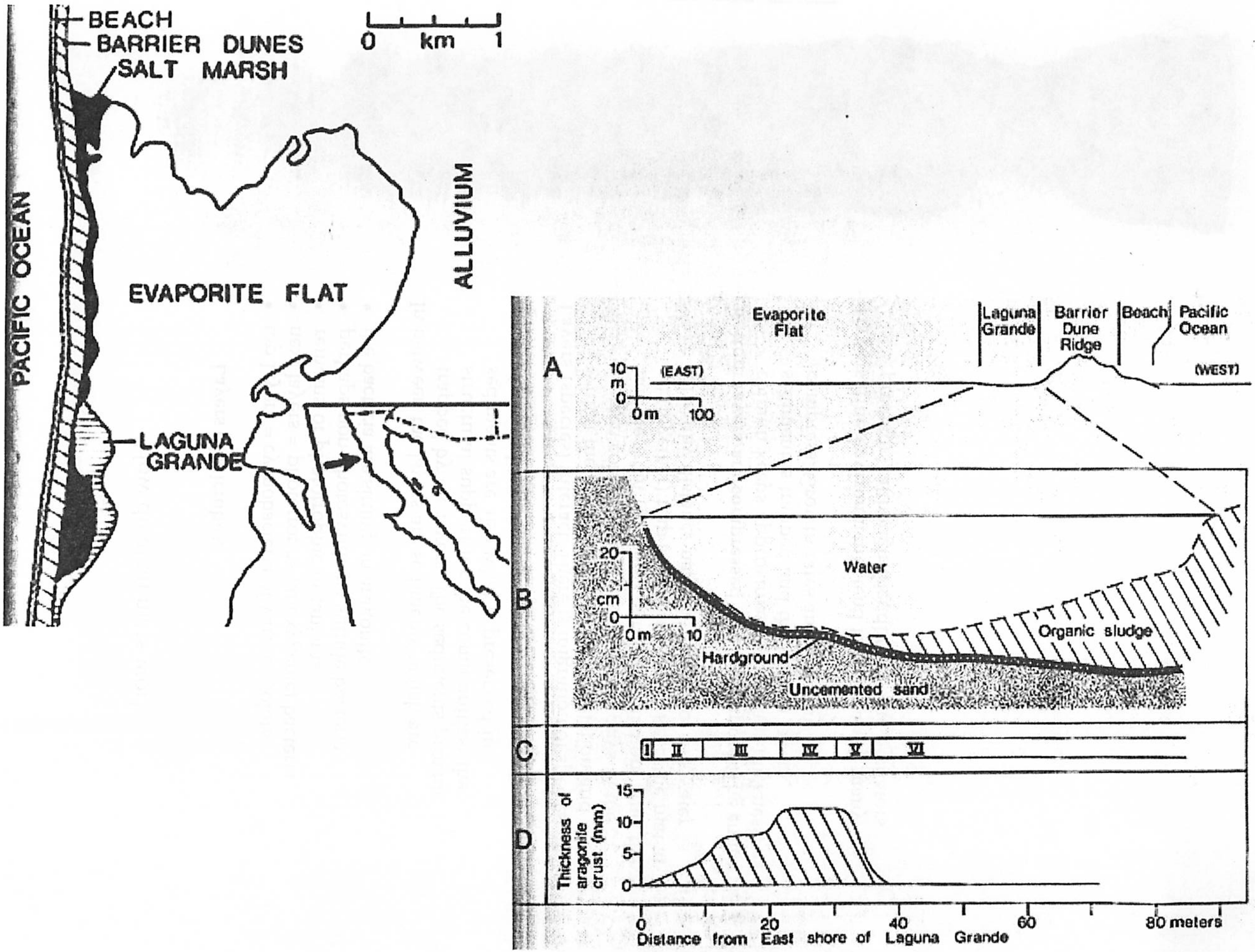
------------------------What is a **stromatolite?**--------------------

A stromatolite is the **STRUCTURE CREATED** by an algal mat. Algal mats trap sediments between the layers, and these sediments are compacted into physical (geological) structures called **STROMATOLITES. STROMATOLITES** are **ORGANOSEDIMENTARY STRUCTURES.**

---------------Why do we care? Why play with the scum?-----------

Algal mats -- or their cousins -- have been around a **LONG** time. The **WARRAWOONA STROMATOLITES** are 3.5 billion years old, the **OLDEST KNOWN FOSSILS** (inferred fossil structures). So we care about them when we care about origins/evolution of life.

We also care about fossils and rocks on earth (see later pages). The proterozoic was the age of cyanobacteria. There's also the origins and history of life connections.



PACIFIC OCEAN
BEACH
BARRIER DUNES
SALT MARSH
0 km 1
EVAPORITE FLAT
ALLUVIUM
LAGUNA GRANDE
A
Evaporite Flat
Laguna Grande
Barrier Dune Ridge
Beach
Pacific Ocean
10 m 0
0 m 100
(EAST)
(WEST)
B
Water
Organic sludge
Hardground
Uncemented sand
20 cm 0
0 m 10
C
I II III IV V VI
D
Thickness of aragonite crust (mm)
15 10 5 0
0 20 40 60 80 meters
Distance from East shore of Laguna Grande

How do algal mats work?

Layers of microbes.

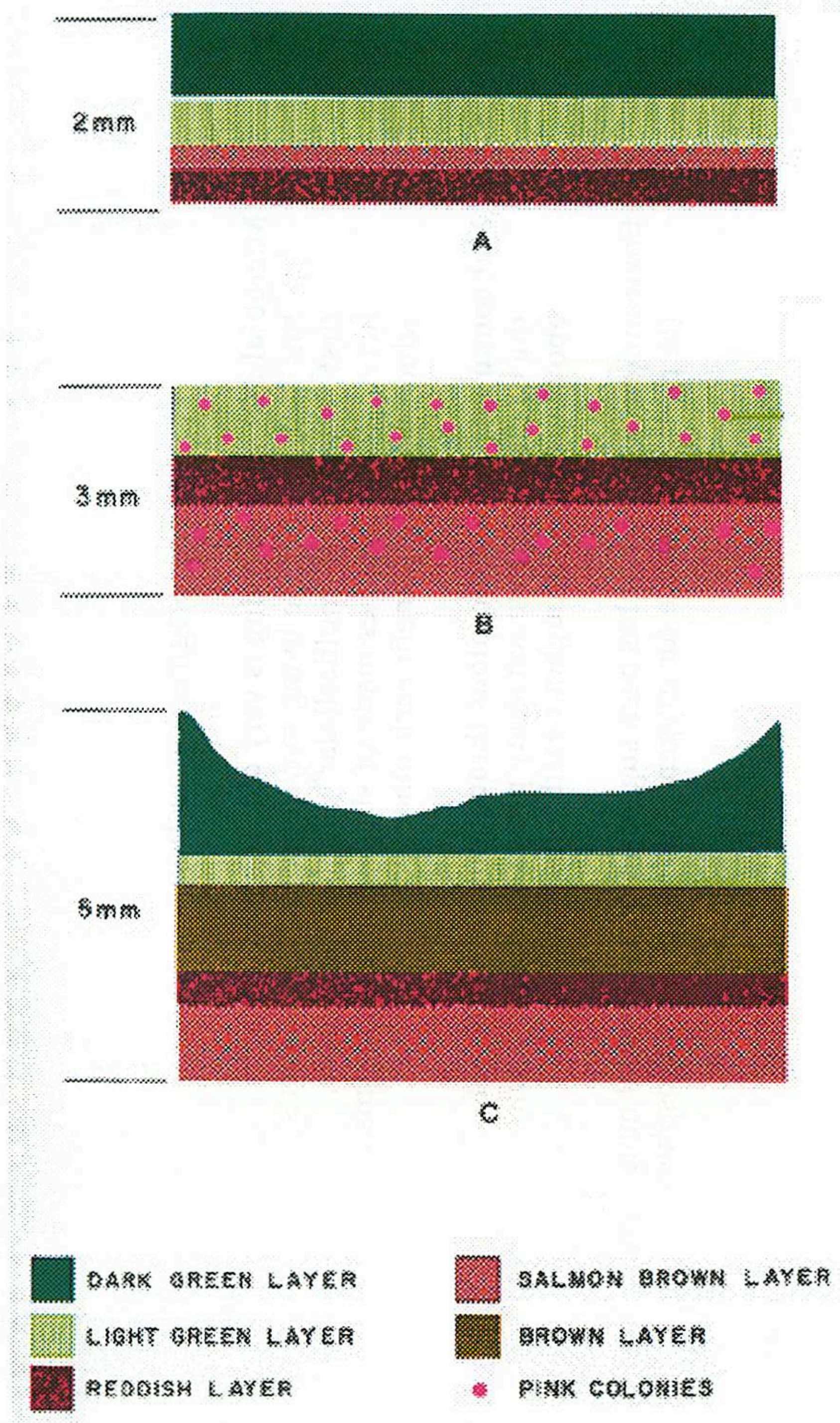
- top layers = cyanobacteria of various colors
- next layers = phototrophs (anoxygenic) bacteria
- remains of phototrophic organisms
- perhaps non-photosynthetic sulfide bacteria
- the bacteria are sitting on aragonite

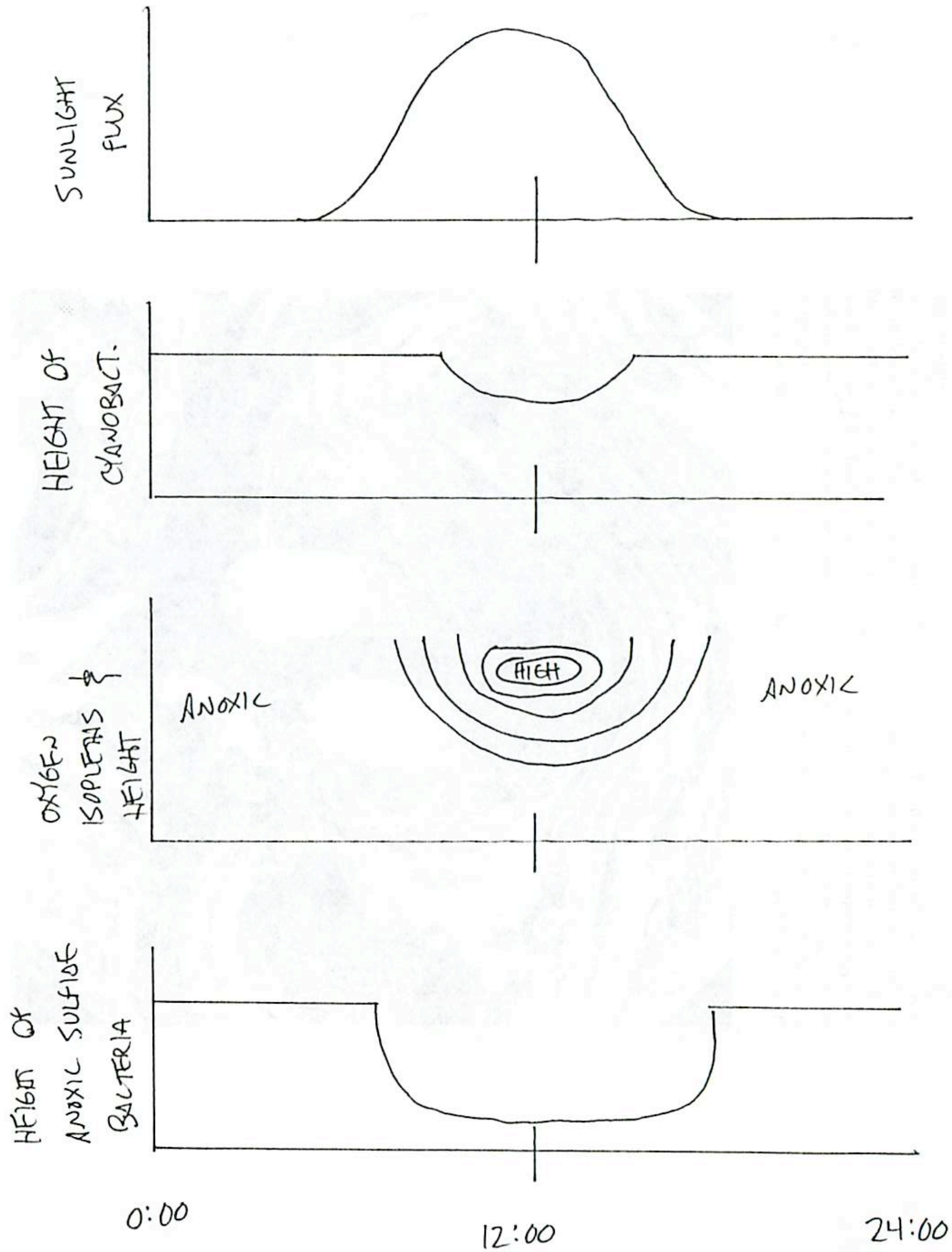
In between the layers are sediments which are trapped by the layers. The sediments provide structural support for the communities; the sediments are also what is preserved in stromatolites.

Layers (species) interact. There is migration of species within the mat, depending on irradiation and oxygen content. Guys on top shield guys in the middle from (to them) harmful radiation. And they all (together) trap sediments which keep the mat at a healthy distance near the surface of the water.

Bottom layers are compressed and decompose. The entire column keeps approximately constant thickness, as sediment is trapped and the bottom layers compress. Growth rates are 5-10 mm/yr.

Hypersaline environments tend to chase away many predators, although friendly to some predators





AFTER GARCIA PICHEL ET. AL. 1994

The origins connection

Microbial mat style of living is very old. The idea is that this kind of microbe living may represent this planet's first "attempt" at 'multicellular" life. In other words, here are communities made of single-celled organisms which mutually benefit each other.

Mat communities are ubiquitous throughout the history of the earth, so that we can study present mats and learn about lifestyles throughout earth's history.

Environmental effects. It has been suggested that microbial mats were (in part) responsible for oxygen build up in the atmosphere

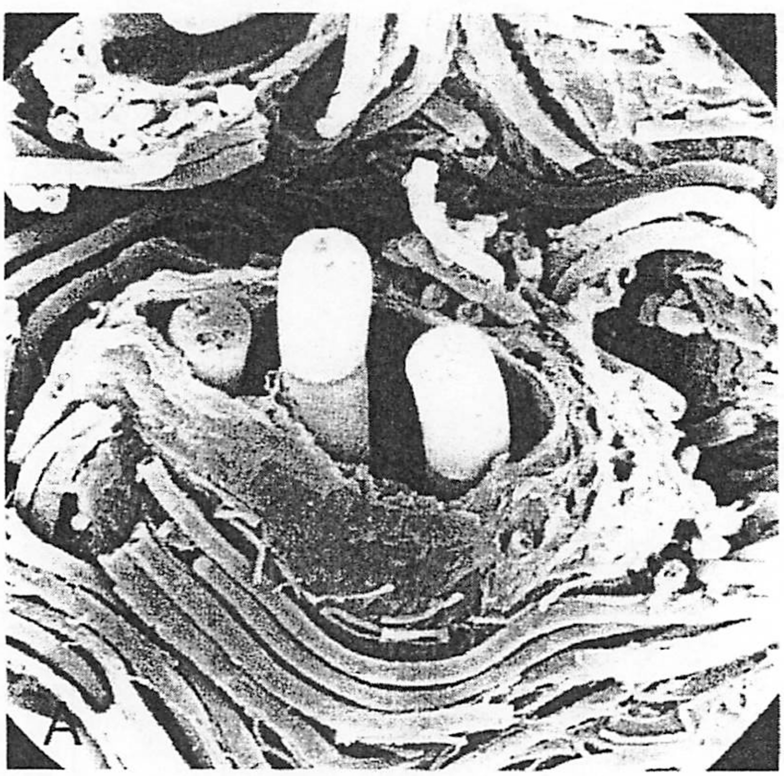
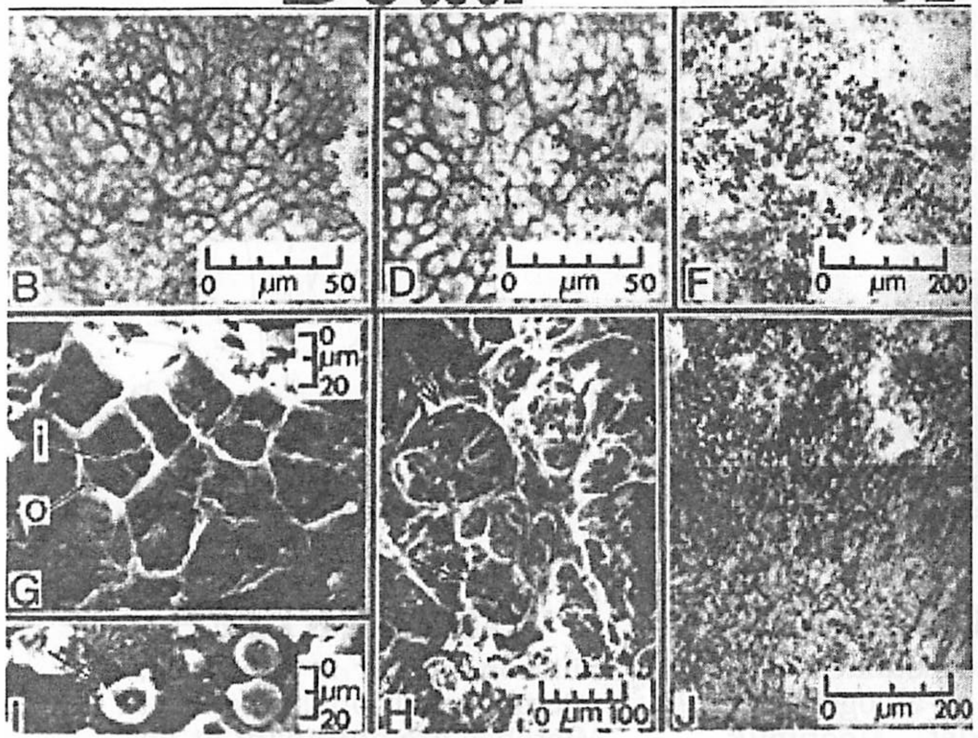


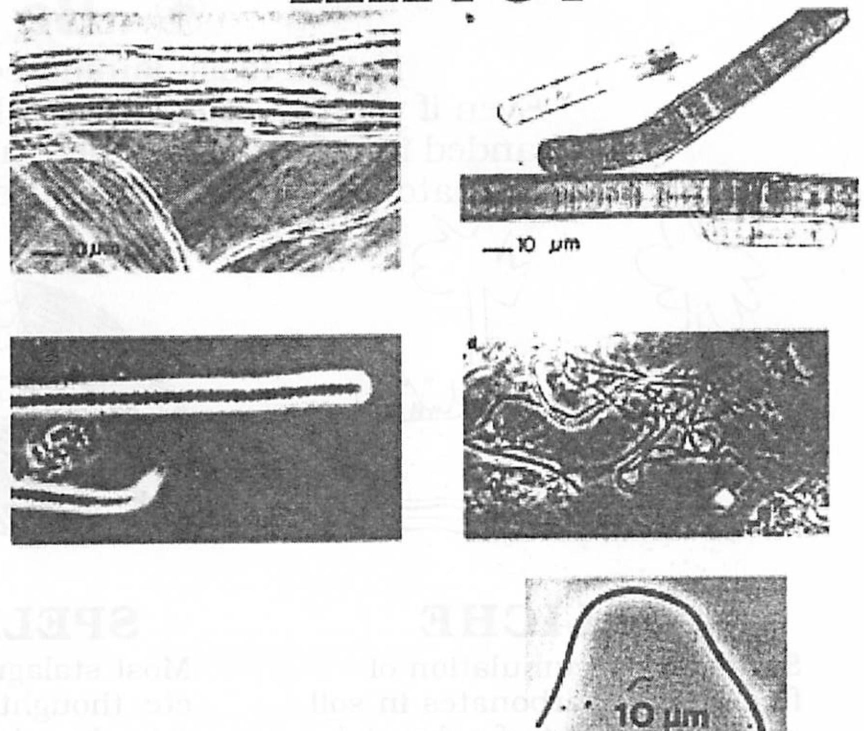
Fig. 3. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) of the *Microcoleus chthonoplastes–Chloroflexus*-type association in the photic zone of the flat shallow mat in Solar Lake. A) Note tight association among the photosynthetic microorganisms. *Chloroflexus*-type is ensheathed. SEM × 3,600, bar = 10 μm. B) Ensheathed *Chloroflexus* type are shown at bottom left side. Note numerous chlorosomes (chlorobium vesicles) in the periphery of each cell. TEM × 7,800, bar = 5 μm. This picture is almost identical to the microbial association shown from Laguna Figueroa, Baja California, Mexico by J.F. Stolz (this volume).

Dead or Alive?



As the organisms die, their cells are filled with the aragonite precipitating on them and are preserved as microfossils. Only the outside structures hold up to the recrystallization process. As the aragonite and fossils are metamorphosed or further recrystallized (aragonite→calcite), the fossil cell structure is lost. Stromatolites are abiophoric, meaning they lack preserved microfossils.

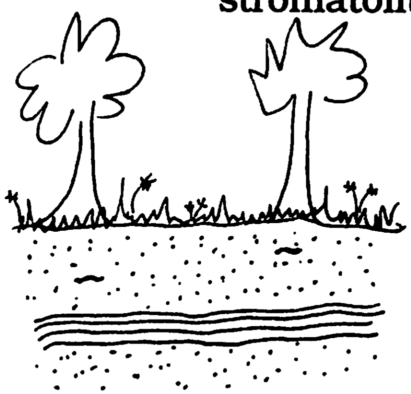
B, D: closeups of thin sections show preferential preservation of sheaths and absence of preserved intracellular material. F: calcite granules in aragonite. G, H, I: *Entophysalis* colonies permineralized by aragonite. Only outer sheaths are preserved well (o, arrow). J: Poorly preserved radiating fabric of *Entophysalis*.

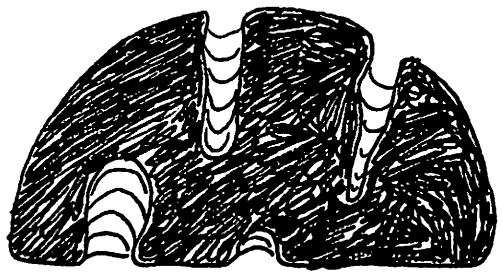


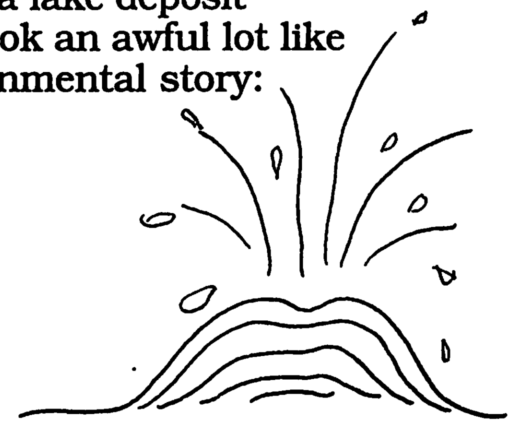
Many different types of microbes can live in the algal mat setting. The top layers are usually cyanobacteria, or photosynthetic prokaryotes (*Microcoleus chthonoplastes, Lyngbya aestuarii, Oscillatoria lloydiana, Oscillatoria longearticulata*). The middle layers are anoxygenic, phototrophic bacteria like *Chloroflexus*, which use the light filtered out by the top layers.

❀ Be careful! ❀

Not all fossil laminated structures are stromatolites!
Even if you can tell that your layered structure is not a lake deposit or a banded iron formation, there are some deposits that look an awful lot like stromatolites but tell an entirely different paleoenvironmental story:







CALICHE

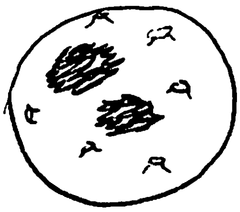
Secondary accumulation of fine-grained carbonates in soil profiles, product of subaerial weathering. Sometimes, the shoreline moves, which can create an alternating structure of caliche/mats (difficult to differentiate!). **Caliche distinguishing characteristics:** show other weathering features like leaching, brecciation; tend to follow existing topography (mats thicken over highs); usually thin, graded layers.

SPELEOTHEMS

Most stalagmites/stalactites, etc. thought of as abiogenic, but microbes do exist. *Moonmilk* is a bacteria-induced breakdown product in caves. **Speleothem distinguishing features:** association with other speleothems; presence of diagenetic carbonate like dolomite; indication of precipitation rather than entrapment.

GEYSERITES

Siliceous sinter is aboigenic, microbanded, opaline silica. Microbes are abundant at hot springs though!! **Geyserite distinguishing features:** form at places of hot water discharge (look for vent sites); micro-cross-lamination due to changing flow directions; extremely thin laminae (0.5-4 mm thick).



The Planetary Connection:

Stromatolites as paleoindicators of geologic change

Stromatolites are the most common and long-ranging fossil in the geologic record. They were favored in the Precambrian when there was not a lot of land mass for things to live on, and organisms probably didn't deal well with UV radiation yet. Algal mat communities flourished in an environment where a few cm of water attenuated UV radiation but allowed photosynthetic light in. Not a good index fossil, as they occur all throughout record without much morphological change, and are abiophoric (lack preserved microfossils). Workers who try to figure out paleoclimates from stromatolites look for form changes, or chemical indicators (alkanes, fatty acids, pigments) to tell if they are dealing with organic fossils.

In theory, stromatolites can be used as paleontological clocks. If they record the length of the sidereal day, you can extract the speed of Earth's rotation. If they record synodic month, you can get the evolution of the Moon's orbit. ***In theory.*** Diurnal laminae are common but not continuous. Seasonal variations sometimes show a better degree of completeness, but still not very reliable. The highest level of stromatolite growth indicates local tidal high (Cloud extrapolated this to the Earth-Moon distance, got the Moon's "closest approach" to Earth in mid-Paleozoic, result disputed). To be a good paleoindicatior of this sort, need four things: ❶be aqueous, quiet water, some physiochemical parameters vary regularly with daily fixed frequencies;❷ be affected by tides but not by strong storm waves;❸ be populated by microbes with diurnal growth and which cause precipitation of a preservable layer;❹ be lacking in other biological systems which are disrupting.

Archean Earth and Early Life

conducted by James Head

The Archean Age

The beginning of the Archean is defined by the earliest known rocks, and thus the absolute age of the Hadean/Archean boundary changes. Currently, the oldest known rocks are gneisses from the Slave Province in Canada that date to 3.96Ga. These rocks are described by Bowring and colleagues in *Geology* in 1990. The end of the Archean occurred approximately 2.5Ga ago. The Archean/Proterozoic boundary is marked by a distinct difference in the degree of differentiation of crustal rocks, in the sense that Proterozoic and later rocks appear to derive from crustal sources while Archean rocks derive directly from the mantle.

Nature of Life

During this time, life appeared to be comprised strictly of prokaryotes, *id est*, organisms whose cells lacked a nucleus. The oldest known fossilized organisms date to 3.5Ga. There is circumstantial evidence of life as ancient as 3.8Ga. This result is based on the apparent fractionation of the stable isotopes of carbon in a sense that is indicative of life. This was the era when green slime ruled the earth.

Climate

The climate during the Archean was temmperate. Liquid water was present on the surface. Data supporting this view include the occurrence of Archean sediments or metasediments and the existence of life. Our presumtion still is that life requires liquid water. Stable isotopes of oxygen and carbon are used as paleoclimate indicators, but I've not heard of their use in this context--the appropiate rocks are unlikely to exist.

Atmosphere

The atmospheric composition was quite different from today. There was little if any oxygen and there must have been some greenhouse gas, probably CO_2, in abundance.

There are many lines of evidence suggesting a lack of O_2 in the atmosphere at this time. Redbeds (highly oxidized rocks) do not appear until the end of the Archean. If the atmospheric was oxidizing during the Archean, redbeds should appear throughout the era. Banded-iron formations (BIFs) appear during the latter part of the Archean. The formation of these massive beds require Fe to be dissolved in the oceans, requiring reduced conditions.

The atmosphere must of had a significant greenhouse component due to the implications of the well-known faint early sun paradox. The sun should have been 25-30% dimmer than it is currently. The present atmosphere under those illumination conditions would result in a global deep freeze. Since we have evidence for water early in earth history, there must have been a stronger greenhouse effect than there is currently (unless the stellar evolution models are significantly flawed). A ten-bar CO_2 atmosphere has been advocated (Kastings' work) to warm the earth. However there are advocates of a significant contribution from methane. Kastings discussed methane production in the presence of a thick CO_2 atmosphere during his colloquium last semester.

The Archean Crust

This is discussed extensively in the text by McLennan and Taylor, particularly Chapters 5, 7, and 10.

The distribution of known surviving Archean terrains is shown in Figure 1. They comprise about 30% of the current continental crust. The very oldest rocks are in Isua (Greenland) and Slave Province (Canada). Studies of the Archean crust suggest that it was similar in thickness to the current crust, contrary to some expectations. It is clear the Archean crust was less differentiated than the current crust. The Archean crust is somewhat depleted in most incompatible elements compared to the more recent crustal rocks.

The growth of continental crust is a subject of vigorous research and contention. It is very difficult to estimate crustal groth by balancing continental crust formation rates with erosion and recycling. These are hard to measure and the erosion rates certainly been influenced anthropogenically. A summary of continental growth models is shown in Figure 2. Everyone agrees that at the beginning there were no continents and that all growth models must converge on the currently observed mass of continental crust. The two present camps are referred to as "fast growth" and "slow growth," (in Arizona I guess these would be Republicans and Democrats).

The slow growth camp (Ross Taylor, Scott McLennan *et al.*) note that there are very few Archean rocks. They maintain that large amounts of Archean crust is not required to explain the geochemical data, so they argue that there is no need to propose it. Some crust did form 3.8Ga, but at most this amounted to 15% or so of the present continental crust.

The fast-growth camp (Sam Bowring *et al.*) point out that the Nd isotopic data requires extraction of crust from the mantle. Fractionation of Sm and Nd during crustal extraction changes the Nd isotopic ratios in the crust and the depleted mantle. Examination of mantle-type rocks in Greenland show such an effect to the same degree seen in much younger rocks. The fast-growth camp argues that this means the entire mantle had this Nd signature in the Archean and that therefore a mass of continental crust even larger than that extant today formed early in the Archean. Slow-growthers counter that the data can be explained by local postulating local depletions instead of global. Fast-growthers point out there are similar data for rocks in Canada. I'd counter that the present day location of rock units says nothing about their geometry 3.5Ga ago. There is widespread agreement that the models represented by Hurley and Hurley and Rand are not tenable in light of K-Ar and Rb-Sr data. The argument lies between the models represented by Taylor and McLennan on the one hand and by Fyfe on the other. Currently, various research groups are re-analyzing the Nd data to see if later metamorphic events could have influenced the interpretation of the results.

The amount of continental crust, hence the area of the oceans, in the early Archean is a controversial question. Credible estimates range from 15% to 130% of the present continental crustal mass. Towards the end of the Arcean there is considerable convergence of opinion and the esimates range from 90% to just over 100%.

For more strange graphs and odd equations about the continental crust, see Taylor and McLennan (1985) *The Continental Crust: Its Composition and Evolution*, Blackwell Scientific Publications.

1.

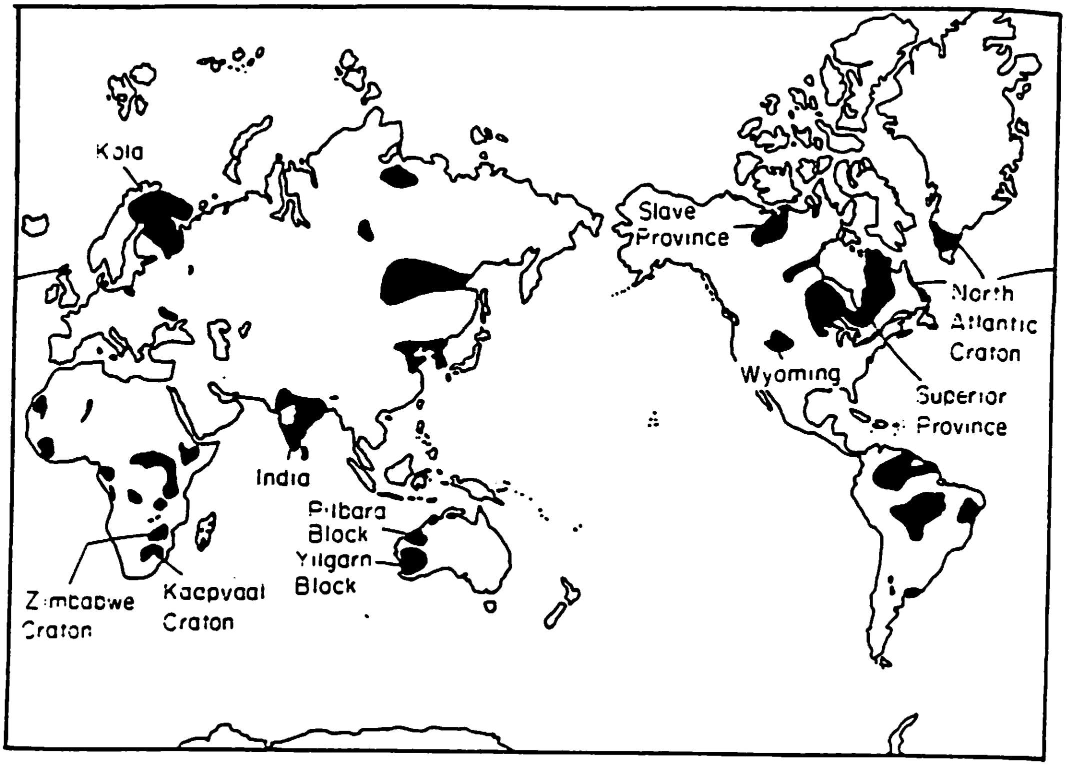


Fig. 7.1. World distribution of Archean terrains.

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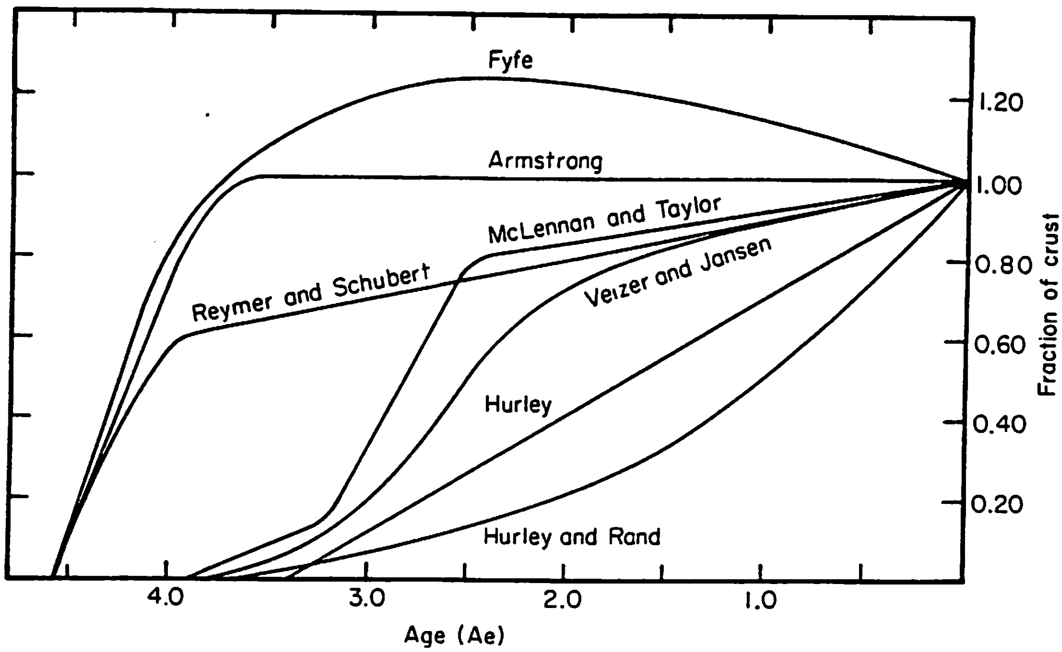

Fig. 10.1. A selection of crustal growth models. Models shown include those of Reymer & Schubert [2], Armstrong [5], Fyfe [15], Hurley [17], Hurley & Rand [18], Veizer & Jansen [20, 23] and McLennan & Taylor [24].

BLUESCHIST METAMORPHISM

Windy Jaeger

OUTLINE

I. Introduction to metamorphism
- A. What is metamorphism?
- B. Brief history of how metamorphic petrology came about

II. What are the 11 metamorphic facies, what characterizes them, and where do blueschists fit into this picture?
- A. P-T diagram showing the 11 metamorphic facies
- B. ACF diagram showing a characteristic basalt mineralogy for each of the metamorphic facies

III. What is the environment in which blueschists form?

IV. Theories on blueschist exhumation

V. Franciscan Group

REFERENCES

Baldwin, S. L. (1989) Geochronology of blueschists from West-central Baja California and the timing of uplift in subduction complexes. *Journal of Geology* **97,** 149-163.

Maekawa, H., Shozui, M., Teruaki, I., Fryer, P., and Pearce, J. A. (1993) Blueschist metamorphism in an active subduction zone. *Nature* **364,** 520-523.

Maruyama, S., Liou, J. G., and Terabayashi, M. (1996) Blueschists and eclogites of the world and their exhumation. *International Geology Review* **38,** 485-594.

Monroe, J. S., and Wicander, R. *Physical Geology*, West Publishing Company, St. Paul, Minnesota.

Philpotts, A. R. *Principles of Igneous and Metamorphic Petrology*, Prentice Hall, New Jersey.

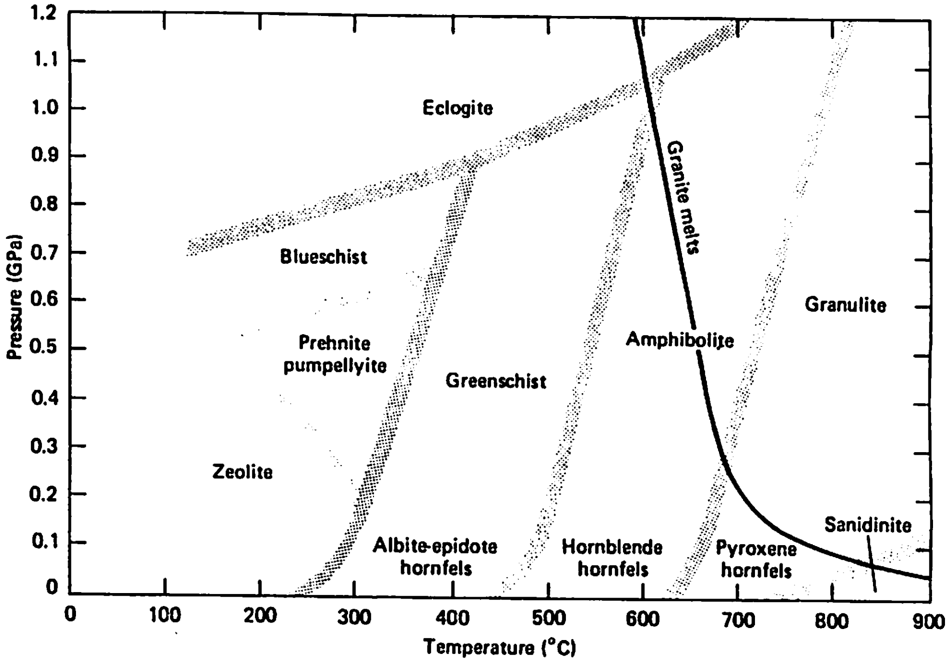

FIGURE 15-6 Approximate pressures and temperatures under which various metamorphic mineral facies form. Rocks are assumed to be in equilibrium with water at the same pressure as the load pressure. Facies are shifted to lower temperatures if partial pressures of water are less than the load pressure. Boundaries between facies are broad zones in which a number of important reactions take place (Fig. 15-7). The melting curve for peraluminous (S-type) granite under water-saturated conditions is from Clemens and Wall (1981).

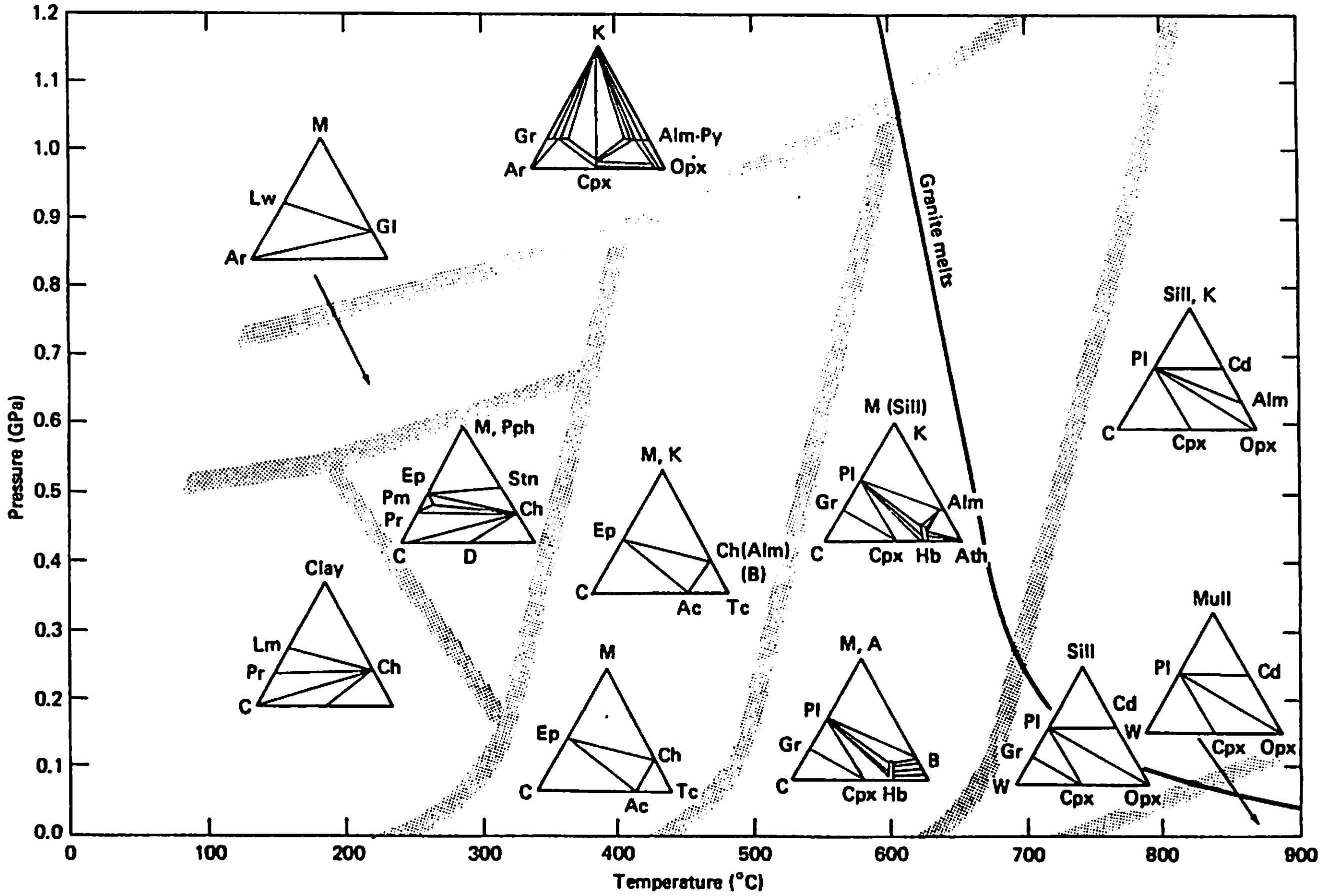

FIGURE 15-7 *ACF* plots of common quartz-bearing mineral assemblages in the metamorphic facies. Boundaries and conditions are the same as in Figure 15-6. Minerals plotted include andalusite (A), kyanite (K), sillimanite (Sill), muscovite (M), mullite (Mull), grossularite (Gr), almandine (Alm), pyrope (Py), orthopyroxene (Opx), clinopyroxene (Cpx), calcic plagioclase (Pl), epidote (Ep), lawsonite (Lw), laumontite (Lm), pumpellyite (Pm), prehnite (Pr), calcite (C), aragonite (Ar), dolomite (D), wollastonite (Wo), actinolite (Ac), hornblende (Hb), glaucophane (Gl), anthophyllite (Ath), talc (Tc), biotite (B), chlorite (Ch), cordierite (Cd), pyrophyllite (Pph), and stilpnomelane (Stn). The beginning of melting curve for water-saturated peraluminous granite is from Clemens and Wall (1981).

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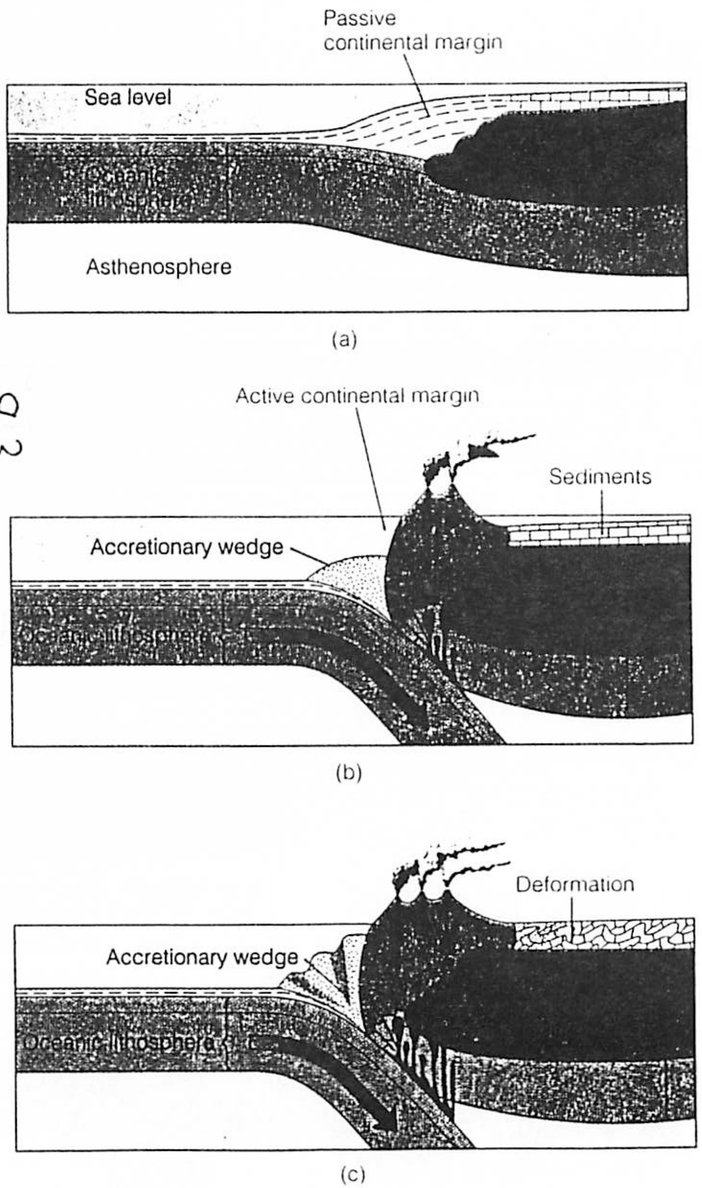


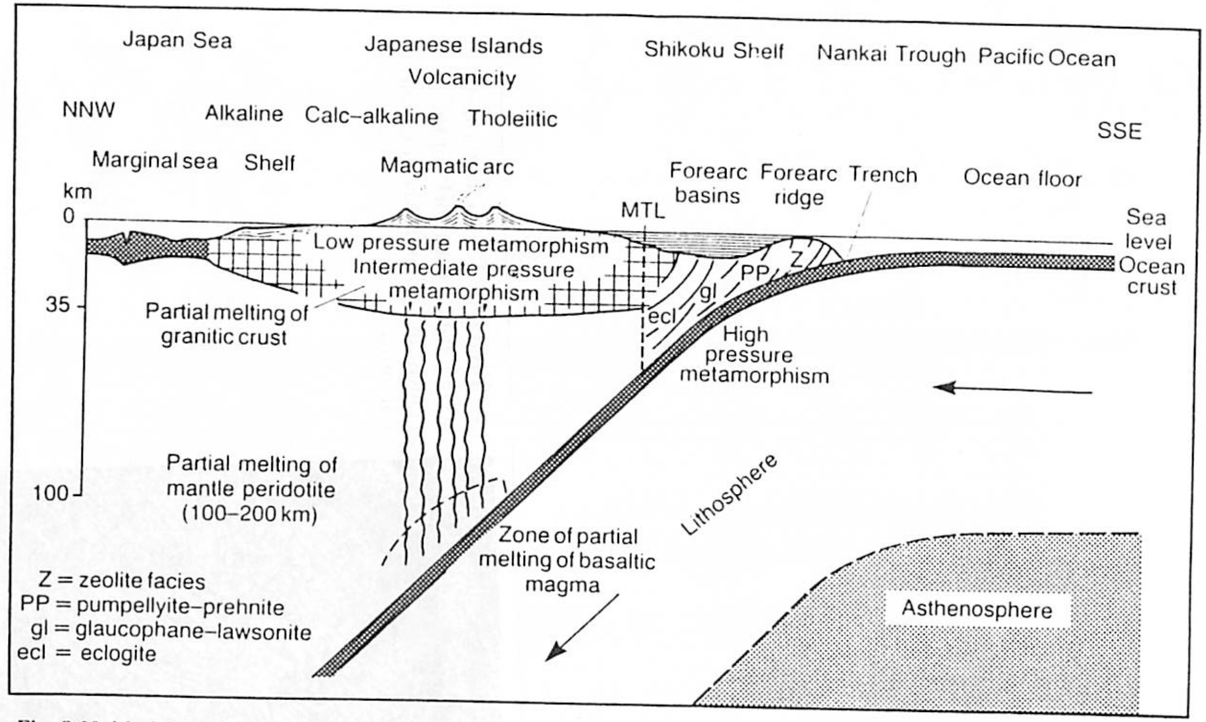


Fig. 8.20 Model for the interpretation of convergent plate margins as applied to SW Japan. MTL, Median Tectonic Line (redrawn from Barber, 1982, with permission from the Geologists' Association).

➢ FIGURE 13-29 Generalized diagrams showing three stages in the development of the Andes of South America. (*a*) Prior to 200 million years ago, the west coast of South America was a passive continental margin. (*b*) Orogenesis began when the west coast of South America became an active continental margin. (*c*) Continued deformation, volcanism, and plutonism.

▶ FIGURE 13-30 Deformed accretionary wedge rocks of the Franciscan Group in Marin County, California.

Adventures in Boredom

Ralph D Lorenz

Britain is almost devoid of spectacular natural phenomena of the active sort, and, on balance is the pleasanter for it. An odd glacier or geyser here and there might not be unwelcome, but who wants volcanos, earthquakes, typhoons, cyclones and the like?.......But we have the bore - that relentless moonchild, the eerie wave that glides, sweeps and crashes its way upstream through the lower reaches of the Severn when tides are high...' Rowbotham, 1964

Shortly after the after the tide had stopped running out they saw something coming toward them from the ocean in a long white line, which grew bigger and whiter as it approached. Then there was a sound like the rumbling of thunder which grew louder and louder as the white line came nearer until it seemed as if the whole ocean had risen up, and was coming churning and thundering down on them, boiling over the edge of this pile of water like an endless cataract, from four to seven metres high, shat spread out across the whole Eastern horizon. This was the pororoca! Branner, 1884

A tidal bore is a wave propagating up a river estuary, heralding the turn of the tide. The bore, unlike regular seaside waves, is essentially solitary (although is often followed by some smaller waves) and the water level continues to rise after it.

A tidal bore is a direct analog in hydrology of a shock wave in aerothermodynamics: a disturbance (the rising tide/Concorde) is being forced through a medium (the estuary/the air) faster than the medium can allow a perturbation (a gravity wave/a sound wave) to propagate. As a result, there is a sharp boundary (bore/sonic boom) across which the state properties of the medium (depth/P,T) have a discontinuity.

The requirements for a bore are a high amplitude tide (thus typically in a resonant basin, like the Bay of Fundy) and a shallow-sloped estuary, such that the projected high-water mark can propagate rapidly. Some shallow seashores, e.g. that at Mont Saint-Michel in France, and the Solway Firth in Scotland, have wall-like tides that, since they are not confined in a river, are not strictly bores.

Some Tidal Bores with Cool Names

Chau Dau	Tsientang, China
Pororoca	Amazon, Brazil
Burro	Colorado, Mexico
Mascaret	Seine, France
Aegir/Eagre	Trent, England

Bores in Literature

The bore-like tide in the Solway Firth is mentioned in Sir Walter Scott's Redgauntlet
The Trent Aegir is mentioned in 'The Mill on the Floss'
Victor Hugo's daughter was killed by the Mascaret.

Things to do at Bores

- Fish - Arrival of the Pororoca was heralded by Cranes, presumably drawn to the fish brought to the surface by the bore's turbulence. Baby Eels, similarly exposed to predation by the bores brought on in spring tides, are a traditional Good Friday meal in the Severn estuary in England.
- Tube Rafting - see web pages below
- Surf - the Severn Bore propagates some 10 miles. At least one surfboard has been broken.
- Get a free ride upstream. In the Tsientang river, fishermen tie their boats into protected piers to shelter against the bore; after it has passed, they release and are carrier upriver (remember the tide continues to rise after the passage of the bore)

Where do Tides Come From?

Tidal forces are due to the radial differential in gravitational field strength. Simplistically, the equilibrium shape of the equipotential surface on a spherical earth is ellipsoidal, with a bulge towards and away from the Moon, with a height of 18cm or so (Isaac Newton took the first stab at this, and obtained a figure of 9 inches).

NB the equilibrium tide essentially equates the horizontal component of (gravity-centrifugal force) to the pressure gradient caused by the change in water level.

The Earth rotates under this bulge, so an observer fixed on the Earth's surface would see the tide rise and fall twice a day (approx), and tides at low latitudes would be highest. In reality, water motions cannot keep up with the motion of the sublunar point, and dynamic effects come into play - including the resonance of basins and coriolis forces. These effects conspire to give some places two tides a day ('semidiurnal tide, M_2', as in England) and others one (the diurnal tide, e.g. Vietnam), while most places have a mix (e.g. San Francisco)

The Sun's tidal effect (proportional to Mass divided by the cube of distance) is about one third of the Moon's.

Large Tides

Maximum tides occur in spring and fall (where the Sun is over the equator, and therefore the track of the sublunar point and the subsolar point are near-parallel and close) at New and Full Moon (syzygy, where the Sun and Moon are pulling together), and when the Earth-Sun and Earth-Moon distances are smallest.

Tides of large amplitude occur in basins which resonate at a harmonic of the tidal excitation frequency (~12 hours). Notable examples are the Severn Estuary in the UK, the Bay of Fundy in Canada, and the Gulf of California. The resonance is due to the propagation time of a wave (+ the tide) up and down the basin [for the Bay of Fundy, 270km long , depth D~60m, a shallow water wave travelling at $\sqrt{gD} = 24\ ms^{-1}$, gets to the end and back in 2.2e4s, or 6.1 hours - a convenient multiple of the 12.2 hour lunar semidiurnal period]

Most of the Gulf of California is too deep for shallow water waves like this to work, but it does behave similarly in that the northern part of the Gulf behaves as a tuned oscillator; with the tide covering it in one quarter of a tidal cycle (Filloux, 1973). At the mouth of the Gulf, for example, the M_2 component has an amplitude of 30cm; this falls to about one third in the middle of the Gulf, but builds to 165cm at the head of the Gulf.

Planetary Connection

Tides are perhaps the most familiar connection between the heavens and human affairs - tides themselves are a planetary connection. More generally, ask Dave Trilling about how tides can push giant planets about....

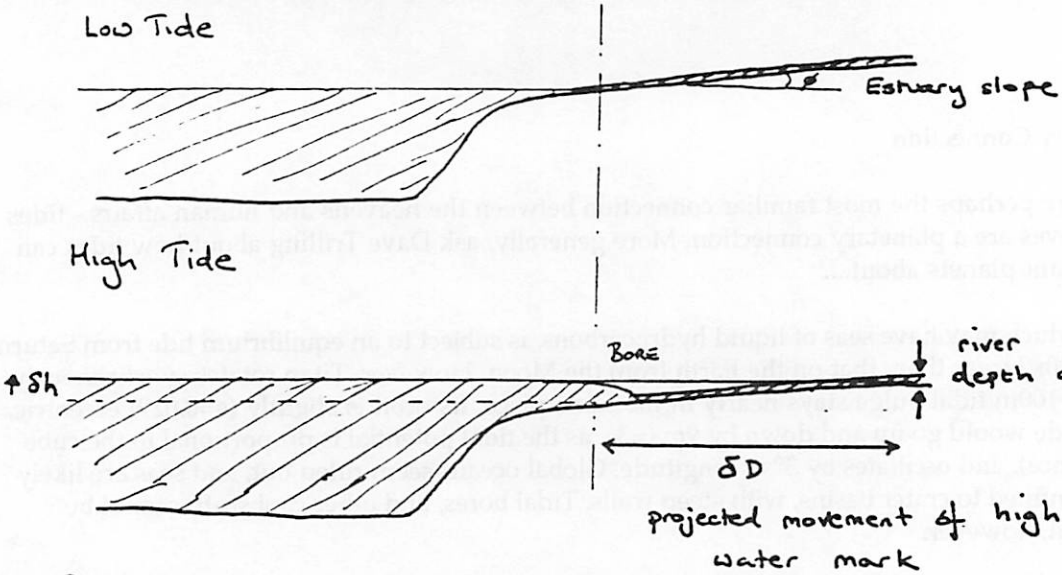
Titan, which may have seas of liquid hydrocarbons, is subject to an equilibrium tide from Saturn some 400x larger than that on the Earth from the Moon. However, Titan rotates synchronously, so the ~100m tidal bulge stays nearly in the same place. Its orbit is slightly (e=0.029) eccentric, so the tide would go up and down by 9m (=3e, as the tidal potential is proportional to the cube of distance), and oscillates by 3° of longitude. Global oceans seem ruled out, and seas are likely to be confined to crater basins, with steep walls. Tidal bores, and other cool stuff, cannot be ruled out, however.

Annotated Bibliography

- Tricker, R. A. R. Bores, Breakers, Waves and Wakes - An Introduction to the Study of Waves on Water, Elsevier New York, 1965 [551.46 T823] *(Marvellous book - nice photographs, descriptions; even straightforward equations and water tank experiments)*
- Waves, Tides and Shallow Water Processes, The Open University, 1989. [GC 211.2 W38] *(A Modern and well-illustrated introduction, with mathematics)*
- D K Lynch, Tidal Bores, *Scientific American* , vol.247, no.4 146-156, 1982 *(good readable account)*
- S Bartsch-Winkler and D K Lynch, Catalog of Worldwide Bore Occurrences and Characteristics, US Geological Survey Circular 1022, 1988 [QE75.C5] *(a comprehensive list of known bores, and a superb bibliography)*
- Rowbotham, F. The Severn Bore [GC 376.R69 - need to get on Interlibrary loan] *(very parochial account, complete with the name of Pubs as landmarks for bore-viewing. Some excellent photographs too)*
- E. P. Clancy - Tides, The Pulse of The Earth, [GC301.C55] *(Good historical background, but not much else)*
- Branner, J. C. The 'pororoca' or Bore of the Amazon, *Science*, v.4 488-490, 1888 *(good old-fashioned - 'I went here and saw this' science)*
- Sykes, G. G. A Westerly Trend, U. of Arizona Press, 1945 [CT 275. S9877.A3] *(Interesting account of an Englishman's wanderings in the Southwest; as well as seeing the bore on the Colorado Delta, he was a member of the Carnegie Desert Laboratory in Tucson, and helped build the dome at Lowell Observatory, etc.)*
- Filloux, A. Tidal Patterns and Energy Balance in the Gulf of California, *Nature*, v.243, 217-221, 1973

Web

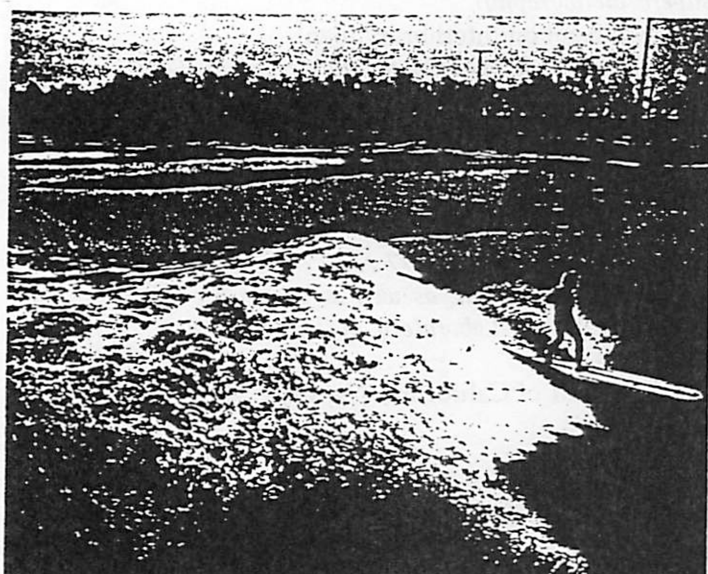
Severn Bore Predictions:
http://www.severn-trent.com/rec_cons/severnbore.htm
Tube-Rafting on Rivers in the Bay of Fundy
http://www.nsis.com/~webmagic/truro/bore.html



Bore occurs (approx) when $\frac{\delta D}{\delta t} > \sqrt{gd}$

or $\frac{\delta h}{\delta t} > \phi \sqrt{gd}$

10 m in 3.5 hrs ~ 10^{-3} ms^{-1} ~ 10^{-3} ~ 3 ms^{-1} for 1 m depth



BORE ON THE SEVERN is the largest in Britain. It is a powerful breaking bore with a crest large enough for surfers to ride upstream for miles. The bore forms near the Severn bridge above Sharpness and extends to Gloucester. Two conditions must be met for a bore to form. First, there must be a broad estuary that narrows toward the river mouth and has a shallow, gently sloping bottom. Such a configuration funnels the incoming tide, increasing its height. The Severn estuary from Cardiff to Bristol has the required narrowing shape. Second, the tides in the adjoining tidal basin must be very high. A difference of more than 30 feet between high water and low water at Sharpness is generally necessary for the Severn bore to form.

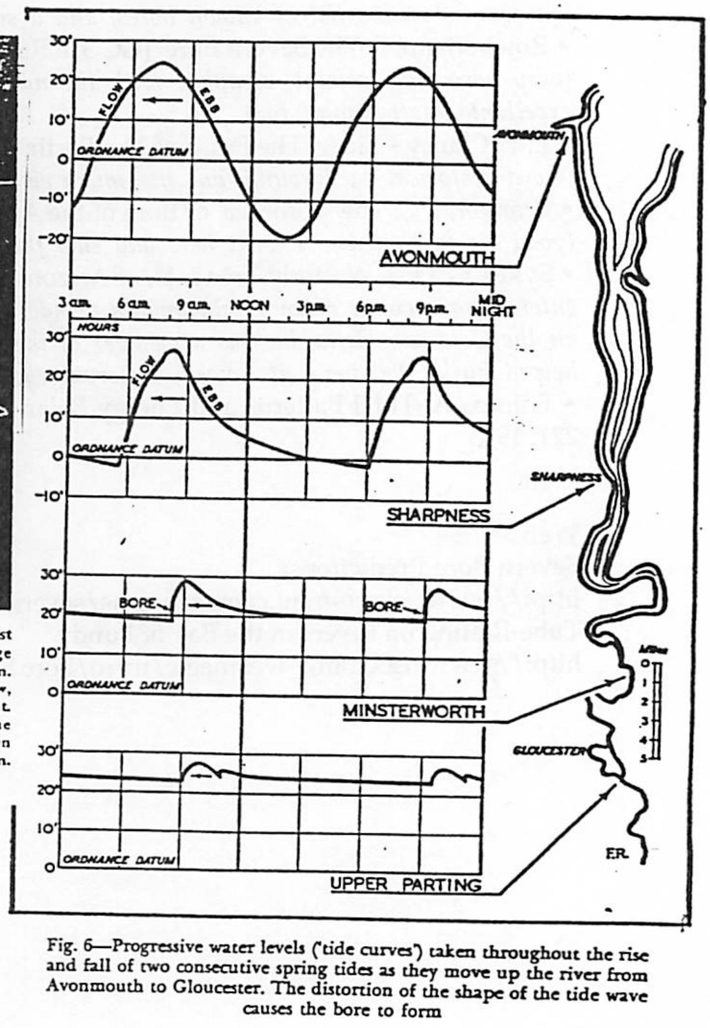
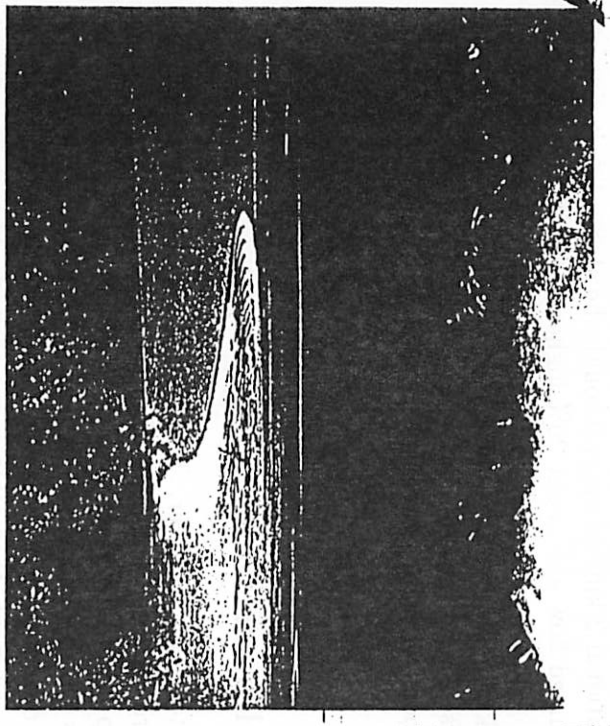


Fig. 6—Progressive water levels ('tide curves') taken throughout the rise and fall of two consecutive spring tides as they move up the river from Avonmouth to Gloucester. The distortion of the shape of the tide wave causes the bore to form



BORE ON TURNAGAIN ARM, near Anchorage, Alaska, is one of the few in North America. It is usually from two to five feet high and, as shown, its leading edge is not straight or uniform. The depth of Turnagain Arm varies greatly. The parts of the bore in deep water move faster than those in shallow water. The faster parts are undular and the slower parts breaking.

TIDAL BORE AT MOUTH OF COLORADO RIVER DECEMBER 8 TO 10, 1923

By James H. Gordon

[Weather Bureau, Yuma, Ariz., December 1923]

The lower delta country, as observed on this trip, is a great level plain so flat that the elevation probably did not vary a foot in the 25 miles crossed. The ruts which formed the road furnished the greatest variation in elevation observed. The plain is almost entirely destitute of plant growth. A liberal estimate would be one small bush to every hundred acres. There was a strong wind blowing. My hat went off. One of the men sprang after it, but was distanced. Because of recent rains it was unsafe to leave the road and follow "cross country." We did not follow the road which trended southeast while the hat went straight south. The hat was kept in sight for more than 3 miles and in that distance there had not been so much as a bush to check it in its mad flight. This to illustrate the character of the country. There are no recognizable channels across it except occasional drainage lines a few inches deep. Water from the Colorado at flood times and from overflow tides must cross this plain to reach Laguna Salada, which they are supposed to feed. The elevation of the plain is given as 8 feet at the northern end and 7 a little distance south of La Bomba.

While crossing this open country Pinto Mountain was observed. It is an isolated peak 1,500 to 1,800 feet high, rising abruptly from the western edge of the plain just south of the entrance to Laguna Salada. It is normally dark in color with its steep slopes grotesquely spotted with big patches of sand, some probably half an acre in extent. Apparently the high north winds blowing down the Laguna Salada Valley pick up nearly their maximum load of sand. Eddies and swirls on the lee side of the mountain check the wind velocity enough to cause a dropping of the sand load. Time did not permit a close study of the mountain.

About 3 miles from La Bomba the road ran into water. It was shallow but extensive, so we left the cars and waded. The water was nowhere more than 6 inches deep, underlaid with a very adhesive mud, and covered perhaps half of the distance. A few "islands" were fairly dry. The rest of the way was mud. The water came from a tidal overflow of two nights previous and would require, we were told, two more days to drain off.

The "city" of La Bomba, the "seaport" of this section of Mexico with two small steamers a week, consists of seven small buildings, including a radio station, and at the time of our visit boasted five inhabitants and seven automobiles and trucks. The "port" is a slushy, crumbling river bank. I did not witness the method of unloading freight but with a normal tidal range of fully 12 feet, strong river and tidal currents and only a crumbling mud bank to work from it must present many difficulties. The freight brought in is mostly liquor for the border towns while fish are shipped south. The "city" is flooded about 6 inches deep every new moon, we were told, and at times of high water in the river it is cut off for weeks at a time. It is soon to be linked with Mexicali by Government-built railroad, much of the grading has been done, but it can never be much of a port. At present it seems to be the only point which may be reached by automobile from which the bore may be observed.

We reached La Bomba at 11.30 a. m. December 8. A strong, cold north wind was blowing and having taken the lay of the land, measured the height of the bank and set stakes by which to judge the bore we took shelter in the lee of one of the houses. A mountain chain of many interlocking ranges lies some 8 miles to the west and was remarkably impressive and beautiful in the sandstorm haze. From our shelter it was possible to see some distance down the river.

The coming of the bore was first called to our attention by the disturbance among a big flock of white pelicans fully 6 miles away. Fish always follow the bore in, we were told. The brown line of the bore itself was visible with the glass at perhaps 3 miles. Its speed appeared to be nearly 8 miles an hour. As a spectacle it was disappointing. This was doubtless due in some measure to the strong north wind that had been fighting the tide all the way up the Gulf. Up to the moment that the bore, or first wave, arrived the current was running strongly seaward. In an instant it was reversed and racing up the river. The bore was not over 3 feet high, a racing wave fully a mile long, foam crested and perhaps a foot higher over the shallows and sand bars. In deep water it was like a ground swell apparently running over the outgoing tide and river current. The *lack of turmoil between the two opposite currents was surprising.* The level of the river rose 3 feet in the first minute and 5 feet in 15 minutes. The bank was 15 feet high at low tide. The high tide of two nights previous had filled the channel and overflowed the surrounding country 6 inches deep. Probably a full half mile behind the first wave something similar to a tide rip appeared, waves 3 to 4 feet high probably not over 20 feet from crest to crest racing up the river. They would have made very rough going for a small boat.

As contrasted with the bore we saw it is said that the first wave is 10 feet high at times. In September, 1922, a small steamer was wrecked by the bore and succeeding waves, with a loss of 130 lives. That is the sort of bore we did not see.

Because of the need of getting back to Calexico that night we did not wait to see the high tide.

Returning from Calexico to Yuma the next day the two other Yuma members of the party and I had opportunity to see the effect of the worst windstorm in years on the sand hills. Where the road crosses this "Sahara of America" the sand-hill area is about 5 miles wide. An eight foot plank road has been built through this section which would otherwise be impassable and an average of about 200 cars pass over it daily. The shifting sands have always been a problem and men with teams and scrapers are maintained at all times to keep the road clear. This storm had been too much for them. Tongues of sand crossed the road in perhaps a hundred places. Where they were not over a foot or 18 inches deep the car took them on the rush but over the most exposed portion of the road the sand drifts were 4 or 5 feet deep. Some 60 cars were tied up when we arrived, some of them had been there 24 hours and our stock of provisions left from trip was quickly disposed of. To the east it was 10 miles to food and water, to the west 5 miles to the headquarters of the road workers. The wind was blowing a gale and the sand was going with it. I have long wanted to watch a storm in the sand hills. This opportunity was ideal save for the fact that for the next six hours we were constantly busy helping others and being helped. In that time we moved forward nearly half a mile, past the worst obstructions and were at last free to go. The impression of a storm in the sand hills is not very different from that of a snowstorm; there is the unending stretch of light grey sand, huge drifts and the air filled with flying particles. I hope to spend a day there a little later in the season with anemometer and single register getting an idea of the wind movement and progress of the dunes. The problem of a road has not been satisfactorily solved and the road department would welcome any definite information. The all-American canal to the Imperial Valley is to go through the sand hills also and the Reclamation Service is anxious to secure data on sand movement as a problem for the canal.

Because of the high wind and sand haze pictures taken on the trip were not entirely satisfactory. I am inclosing a few of the best secured.

LEE ON EVAPORATION LOSS FROM WATER SURFACES: MOIST SOILS, WITH SPECIAL REFERENCE TO CONDITIONS IN WESTERN AMERICA

By A. J. Henry, Meteorologist

[Weather Bureau, Washington, March, 1924]

[Abstract]

The author writes from the standpoint of the practical hydrologist rather than from that of the physicist. After directing attention to the increasing needs for more accurate measures of evaporation he stresses the necessity for the adoption of standard methods of observation, a subject to which further reference will be made later.

pp98-99 Vol. 52 1924

The Colorado River Delta

Where the Grand Canyon went!

with your plausibly helpful host, Andy Rivkin

1 A few words about the Colorado River

The Colorado River is a river of superlatives and, well, anti-superlatives. It has the largest elevation change of any North American river, about 4200 meters from source to mouth. Its length is 2300 km, the seventh longest in the United States. Its basin is larger than France, at nearly 100,000 square kilometers (that's nearly 10^{11} ares, for you strict SI fans).

Despite these numbers, the Colorado only carries 20ish km^3 (or so) of water per year, compared to 240 km^3 for the Columbia River, and 490 km^3 for the Mississippi (Carrier, 1991, as is most of this section). Because the region the Colorado drains is so arid, it is one of the saltiest American rivers, carrying 8 billion kilograms of the stuff each year. Its salinity, which starts at 50 ppm near its source, reaches 700 ppm (that's nearly 0.1%!) at Imperial Dam, north of Yuma. For comparison, the U.S. standard for potable water has a maximum of 500 ppm salt. It also is potentially one of the siltiest rivers in America, with a pre-dam load of 350 million kilograms per **day**. The multiple dams now on the Colorado have cut that figure way down, of course, with whatever is collected below Lake Mead dropped at the All-American Canal (Thompson, 1968).

They have also cut down on the water actually coming through the river channel. The Colorado River Compact in 1922 awarded about half of the river's presumed flow (9.3 km^3) to the upper basin states of Wyoming, Colorado, Utah and New Mexico and the rest of the Colorado's water, plus the Gila's water (total of 10.5 km^3), to the lower basin states of Arizona, Nevada and California. In the 1940's, the Republic of Mexico, negotiated a treaty with the U.S. recognizing their right to some of the water, too. Mexico got rights to an additional 2 km^3 of water, though the states didn't give up any water to make that possible. The presumed flow was about 20% higher than the flow actually has been for the last 70 years, also. Oops. Lots of water gets lost unused, as well: 2 km^3 lost to evaporation from reservoirs, another cubic kilometer lost as runoff into the salton sea after used as irrigation for farms, 86 million cubic meters seeping into the dunes from the All-American Canal. The delta region, once a series of green lagoons with tons of egrets, jaguars, and wild melons, now is basically dry.

But enough of that.

2 Delta Formation (from Plummer and McGeary):

Deltas form when streams or rivers flow into standing water. The river's velocity decreases upon reaching the standing water, and the river drops carried sediment. This sediment builds up, forming the foreset beds of the delta. This build-up eventually reaches the point where a flat top surface is formed, where finer-grained topset beds can be laid down. Commonly, distributaries (small channels carrying water from main channel over surface of delta) are found. Because distributaries can block their own channels by depositing sediment, they often move around. The unique shape of the Mississippi River delta is due to constant dredging of distributary channels, not allowing them to shift (and submerge New Orleans). The shape of most deltas is due to a balance of sediment supply vs. waves and currents from the sea/ocean. See Figure 10.32, from Plummer and

McGeary for an internal view of a simple delta, and Figure 40, from Hazlett, showing the steps in the formation of a lava delta, a similar process.

3 The Colorado River Delta

The area of the Colorado River Delta is shown in Figure 1, from Thompson (1968). The delta fills the northern part of the Salton Trough. Its crest goes southwestward from its apex near Yuma through the Cerro Prieto volcano and Sierro de los Cucupas, with a minimum crest height of 12 m (Muffler and Doe, 1968). It slopes down from its crest (unsurprisingly), to the Sea of Cortez (Gulf of California) with a gradient of 0.35 m/km and to the Salton Trough in the north with a slope of 0.8 m/km (Thompson, 1968). Through its history, the river seems to have flowed both northward and southward, which is extremely unusual. The delta seems to have been built through transient drainage channels that quickly became blocked. After blockages, floods then occurred, causing the river to breach its banks and levees and find a new course down the cone. Usually the new course was simply a lateral diversion, but occasionally the river followed the steeper gradient into the Salton Trough. In the natural case, this would continue until the lake level raised too high, and water poured out again, or until the river channel filled in again (Muffler and Doe, 1968). For the human-aided case, see Spitale, this volume.

Before 1905, the Colorado occupied a meander belt along the Sonoran Mesa, and emptied into the Sea of Cortez in a location similar to the present. Since 1909 (to at least 1968) the Colorado has had no clear-cut channel across the delta. There are extensive secondary delta cones seaward of the mid-delta, where much of the sediment load is dropped (Thompson, 1968).

The delta has existed since the Pliocene, perhaps as far back as the mid-Miocene (15 Mya). The thickness of the delta sediment and sedimentary rocks is about 6 km thick. The sediment currently seen is mostly calcite and dolomite, with fragments of volcanic rock. All of these are uncommon in the surrounding ranges. There is also great mineralogical uniformity in the sediment, leading Muffler and Doe to conclude the area is dominated by Colorado River sediment that has travelled long distances- from the Colorado Plateau. Lead and Strontium isotopes give Precambrian ages, leading them further to conclude that this was igneous material reworked as Mesozoic or Paleozoic sediment, then carried by the river.

In other words,

$$\text{Colorado River Delta} = 1 - \text{Grand Canyon}$$

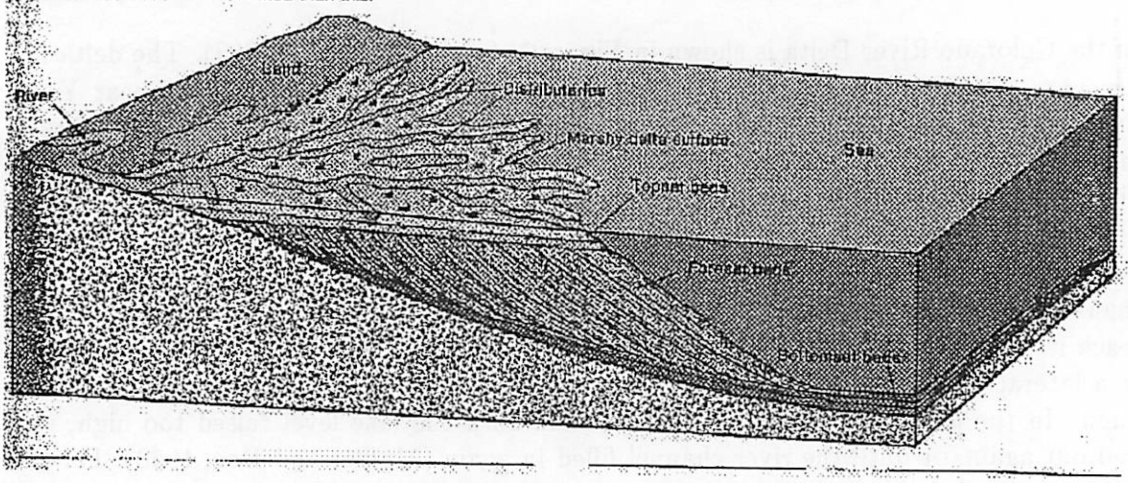
Pretty cool, eh?

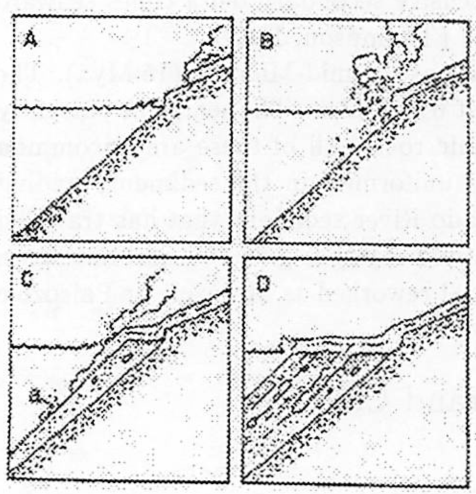
4 The Planetary Connection

Hmmm. Because standing water seems necessary for deltas (even lava deltas), the possibilities are pretty slim. There's the usual standby- Mars, if water stayed around long enough. Titan is popular since we've never seen the surface, but it's unlikely the energy available for sediment movement is enough to do anything (Lorenz, personal communication). Conversely, the identification of a delta on the Martian (or any planetary) surface would indicate long-lasting sediment transport, or in the case of a lava delta, longish-lasting standing water.

References: Carrier (1991), *National Geographic*, June 1991. Muffler and Doe (1968), *J. Sed. Petr.*, **38**. Thompson (1968), *GSA Memoir* **107**. Plummer and McGeary (1988) *Physical Geology*, Wm C. Brown, Dubuque. Hazlett (1993), *Geological Field Guide- Kiluea Volcano*, Hawaii Natural History Association.

Figure 10.32 Internal construction of a small delta. Most large deltas are more complicated than this.





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Thanks, LaTeX!

Figure 40:
Frames A through D illustrate in cross-section the construction of a lava delta as a pahoehoe flow enters the sea. "Foreset bedding" ("a" in Frame C) is built up by the accumulation of breccia, pillow lava, black sand, and other material derived from the flow front by steam blasts, collapse, wave action, and related processes. This debris slope serves as a platform for the nearly horizontal seaward advance of a subaerial flow (the "topset bedding" of the delta), and the growth of new land.

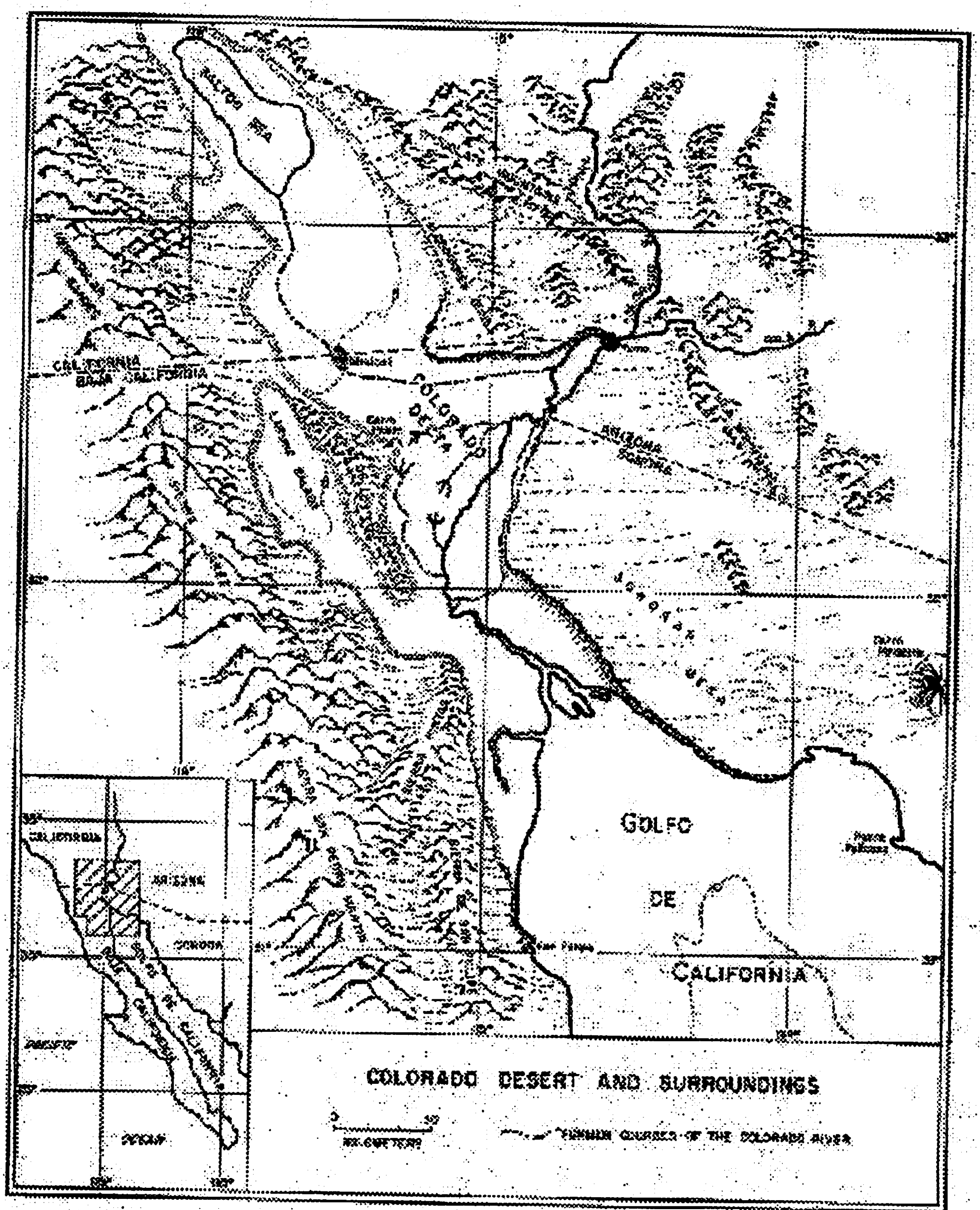

FIGURE 1. Location of Colorado Desert and physiographic features of the surroundings.

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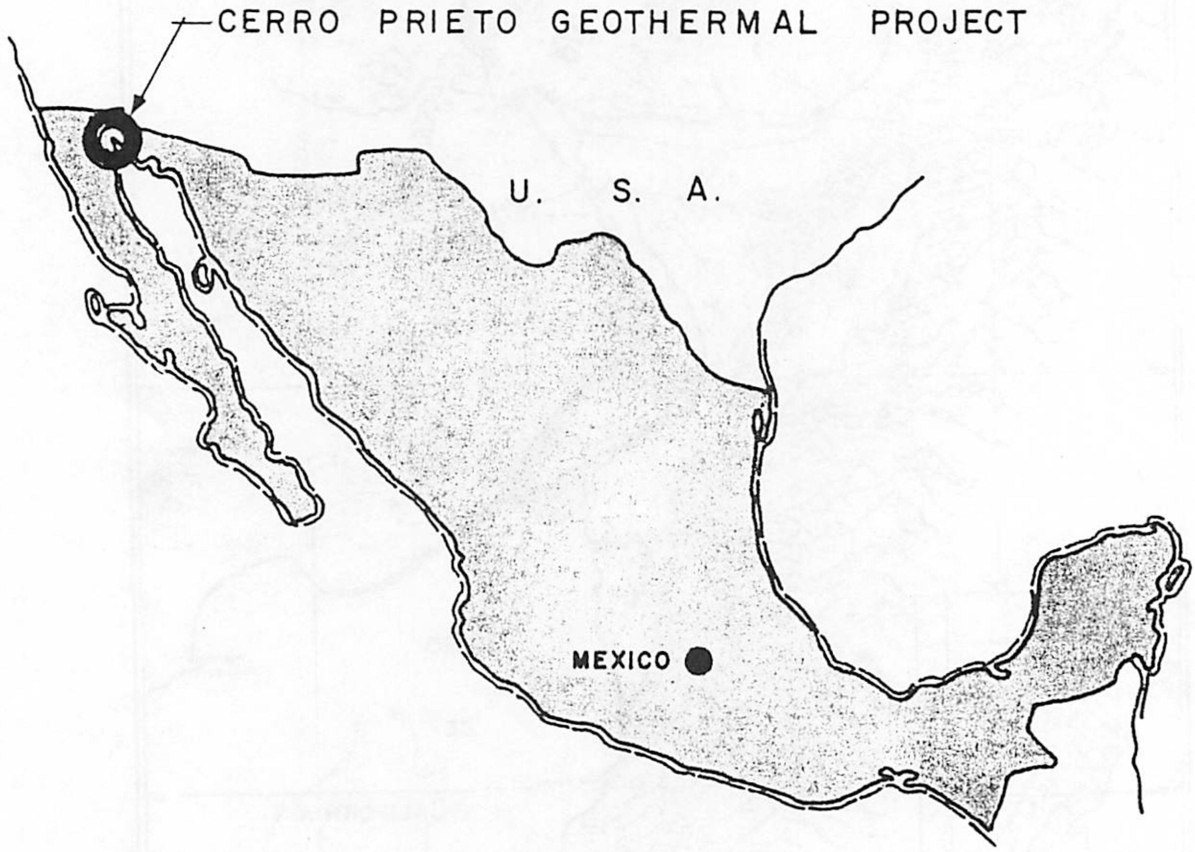
CHAPTER 2

MEXICO



Geothermal Steam and Earthquakes: A Shaky Connection?

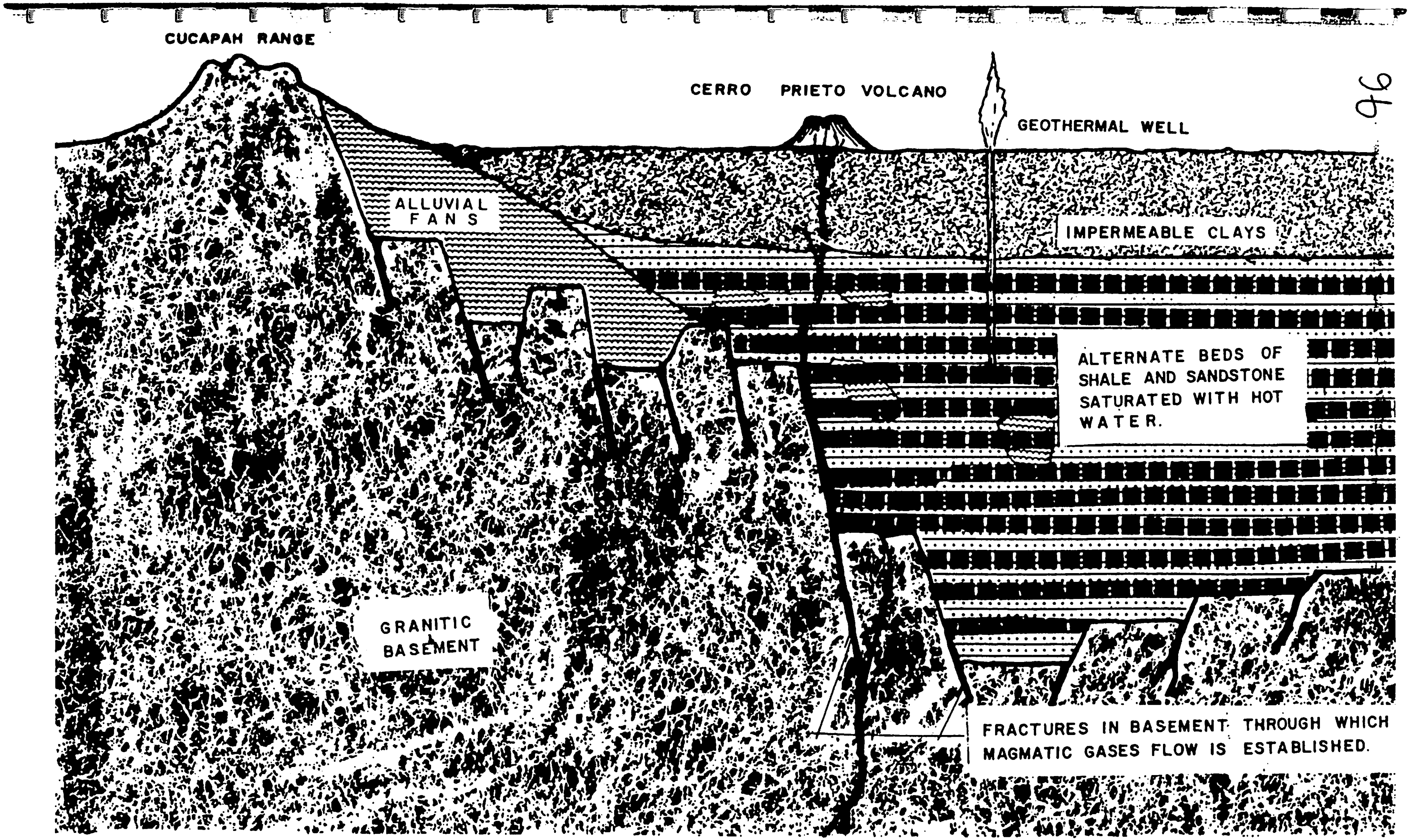
A brief introduction to the Cerro Prieto geothermal field, its history, geology and recent speculations about tectonic activity possibly being related to fluid extraction at the field.

Cerro Prieto Geothermal Field-

Beginning in the early 1950s, the Mexican government, specifically, the Comision Federal de Electricidad, started to explore how to best utilize the geothermal resources of the country. Their first project was the establishment of a geothermal electric production facility at Cerro Prieto.

The geothermal field is located in the Mexicali Valley, Baja California in the southern part of the Salton Trough between the Imperial and Cerro Prieto faults. This area is over the Pacific-North American plate boundary and is tectonically active, providing the heat source for the field. The field is about 30 Km southeast of the city of Mexicali on the Colorado river's delta plains. It is thought that a magma chamber around 5-6 km down provides the heat for the field.

In 1964, four deep (~1300 m) exploratory wells were drilled and large quantities of steam and water were found, so a full-scale facility was built. Electrical power production began in April, 1973, with an initial output of 75 MW. Since this time, production rate growth has been achieved by annually increasing the number of wells on line. By 1993, there were an average of 113 wells on line at any given time, distributed through three



SKETCH OF SUPPOSED GEOLOGICAL CROSS SECTION

Sketch courtesy of Comision Federal de Electricidad.

production areas.

The wells extract steam and water at temperatures in the 250°C- 350°C range, with salinities around 2%, from depths between 1500- 3000 meters. The wells have high production, going from 50 to 117 tons per hour of separated steam. Since going on line, the facility has extracted more than 1 km^3 of fluid and the electrical production capacity has been increased to 620 MW. This makes the Cerro Prieto the second-largest geothermal power-producing plant in the world as of 1993.

Geology of the Cerro Prieto Geothermal Field-

The geology of the field has been fairly well determined through core samples obtained from the drilling of the wells. The regional structure is a tectonic trench which rises in a series of stepped blocks to the west and descends abruptly to the east of Cerro Prieto where the basement crystalline rocks (a granite) are displaced downward by about 3000 m. This basement rock is broken through by a series of northwest-southeast faults, part of the Imperial and Cerro Prieto fault system. These faults through the basement rock provide upflow channels for the high-temperature water. Above the basement rock, there are layers of sandstones and lutites. Overlying this for the first 700 m down are layers of impermeable plastic clays. The sandstone layers are saturated with the heated water, which is forced to flow horizontally away from the upflow zones. The water flow is mainly to the west, thanks to flat stratification and good permeability in the sandstone in that direction. To the east the strata are more compacted and less permeable, so it tends to be self-sealing.

Fluid Withdrawal causing Earthquakes?

In 1994, a theory was proposed that large (> M 5.0) scale earthquakes in the Cerro Prieto area could have been caused in part or whole by the exploitation of the geothermal field and the extraction of fluids that use of the field entailed. A study was conducted from August 1994 to December 1995, using 4 analog seismographs as well as permanent stations from regional networks located on both sides of the border. This first study found no significant links between seismicity and fluid extraction, however another study conducted later seems to have found a possible connection.

The second study looked specifically at three large earthquakes, and when they occurred in relation to large increases in sustained fluid extraction. After about 1 year, in each case of increased extraction, a quake occurred. The study used statistical analyses to determine if there was indeed a link between the two events. These analyses showed that while there was a high probability that the quakes were due to tectonic loading alone, there was also a high probability of triggering due to volume extraction coincident with event occurrence. While the study found that there was a correlation between increased fluid extraction and seismic events, the data were insufficient to conclusively prove the hypothesis. Still, there does appear to be a link and further studies are certainly indicated.

Bibliography

1. Birsic, Rudolph J. More About Geothermal Steam. 1976.

2. Mahon, W.A.J.; Ellis, A.J. Chemistry and Geothermal Systems. 1977.

3. Seamount, Daniel. Well Log Study of the Hydrothermally Altered Sediments of the Cerro Prieto Geothermal Field, Baja California, Mexico. 1981.

4. Glowacka, E.; Nava, F.A. Major Earthquakes in Mexicali Valley, Mexico and Fluid Extraction at Cerro Prieto Geothermal Field. *Bulletin of the Seismological Society of America*. V. 86 No. 1A. 93-105. 1996.

5. Fabriol, H.; Munguia, L. Seismic activity at the Cerro Prieto geothermal area (Mexico) from August 1994 to December 1995, and its relationship with tectonics and fluid exploitation. *Geophysical Research Letters*. V. 24 No. 14. 1807-1810. 1997.