Lunar and Planetary Laboratory
Department of Planetary Sciences

White Sands and Black Caverns

in Southern New Mexico

Planetary Geology Field Practicum

PtyS 594a

Spring 1997

The University of Arizona
Tucson, Arizona

Planetary Geology Field Practicum

Spring 1997

Contents

This Guide Book is produced as part of the Planetary Sciences course PtyS 594a - Planetary Geology Field Practicum given at the University of Arizona, Tucson, Arizona. © 1997
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Responsible Faculty Members: none

Lead Trip Researcher: David Trilling
Guide Book Editor: Eric Wegryn

The Development of the Planetary Sciences Field Trip

Over the past ten years, geology field excursions have become a key part of the graduate education offered by the University of Arizona Department of Planetary Sciences. The concept has evolved from early *ad hoc* trips to an established university course offering, PtyS 594a, Planetary Geology Field Practicum.

This semester the planet we've chosen to explore is (once again) Earth. In addition to the obvious reason for choosing Earth year after year (the fact that Earth is generally considered the most interesting and relevant planet for us to study), there is the lesser known (but very real) problem of funding -- to date, the department head, in league with the Dean of Science, has refused to allocate sufficient funds to mount a field excursion to any other planet. So, with our sights set a little closer to home (for now), we embark this semester upon a trek to Carlsbad Caverns, White Sands, and other geological targets in and around southern New Mexico.

The Father of the LPL field trip is the venerable Professor H. Jay Melosh. Following the example of the Lunar and Planetary Laboratory founder and field trip enthusiast Gerard Kuiper, Jay incorporated field excursions into his Planetary Surfaces course (PtyS 554) shortly after arriving at LPL from SUNY Stony Brook in 1982. The first and most obvious target for field study was Meteor Crater in northern Arizona, which has remained an integral part of PtyS 554, offered every two years, right to the present time. As the course was developed further, a second field trip was added, to the Pinacates volcanic field in Sonora, Mexico.

In 1988 a new idea was proposed: *ad hoc* field trips to fill the gaps between years when PtyS 554 was offered. With strong support from the graduate students, who were now asked to do the background research, a trip was organized to the Grand Canyon. The trip turned out to be, in Jay's words, a disaster. It was almost constantly cold and rainy, and soon became the first (and only) field trip to be aborted. But the idea was a solid one, and other trips were organized in the following years, to the Chiricahua mountains, Canyonlands, and the Superstition mountains (which was led by David Kring in Jay's absence).

The Practicum became an official part of the curriculum in the Fall of 1991, with the first excursion to the Nevada Test Site to observe nuclear explosion craters. Since then they have taken place almost every semester, and have become nearly legendary among students, faculty, and the university motor pool. The student researched topics were eventually combined into a packet of handouts, which has since evolved into this very guide book. There is now even an Internet site for the field trips (www.lpl.arizona.edu/grads/fieldtrips/fieldtrips.html). Over the years the students have taken on more and more of the responsibility, and this semester, with Jay on sabbatical, we embark upon the first PtyS 594a trip organized almost entirely by the students.

As mentioned earlier, funding constraints still require us to choose Earth every semester. But this may be changing. The field trips have been continually increasing in scope and profile, and, thanks largely to the tireless lobbying efforts of Jennifer Grier, next semester's trip to Yellowstone National Park will be the biggest and longest trip (with the largest funding allocation) ever. So perhaps it will not be too long before the Planetary Geology Field Study lives up to the full implications of its name.

Eric Wegryn

Past Planetary Sciences Field Trips

1983	S - PtyS 554 Planetary Surfaces
1984	none
1985	S - PtyS 554 Planetary Surfaces
1986	none
1987	S - PtyS 554 Planetary Surfaces
1988	S - Grand Canyon
	F - Chiricahua Mountains
1989	S - PtyS 554 Planetary Surfaces
1990	S - Canyonlands
	F - Superstition Mountains
1991	S - PtyS 554 Planetary Surfaces
	F - Nevada Test Site
1992	S - Canyon d'Chelly / Petrified Forest
	F - White Sands / Chiricahua Mtns.
1993	S - PtyS 554; Southern California
	F - Superstition Mountains
1994	S - Grand Canyon
	F - Southern California coast
1995	S - PtyS 554 Planetary Surfaces
	F - Nevada Test Site
1996	S - White Mountains
1997	S - White Sands / Carlsbad Caverns

S - spring F - fall

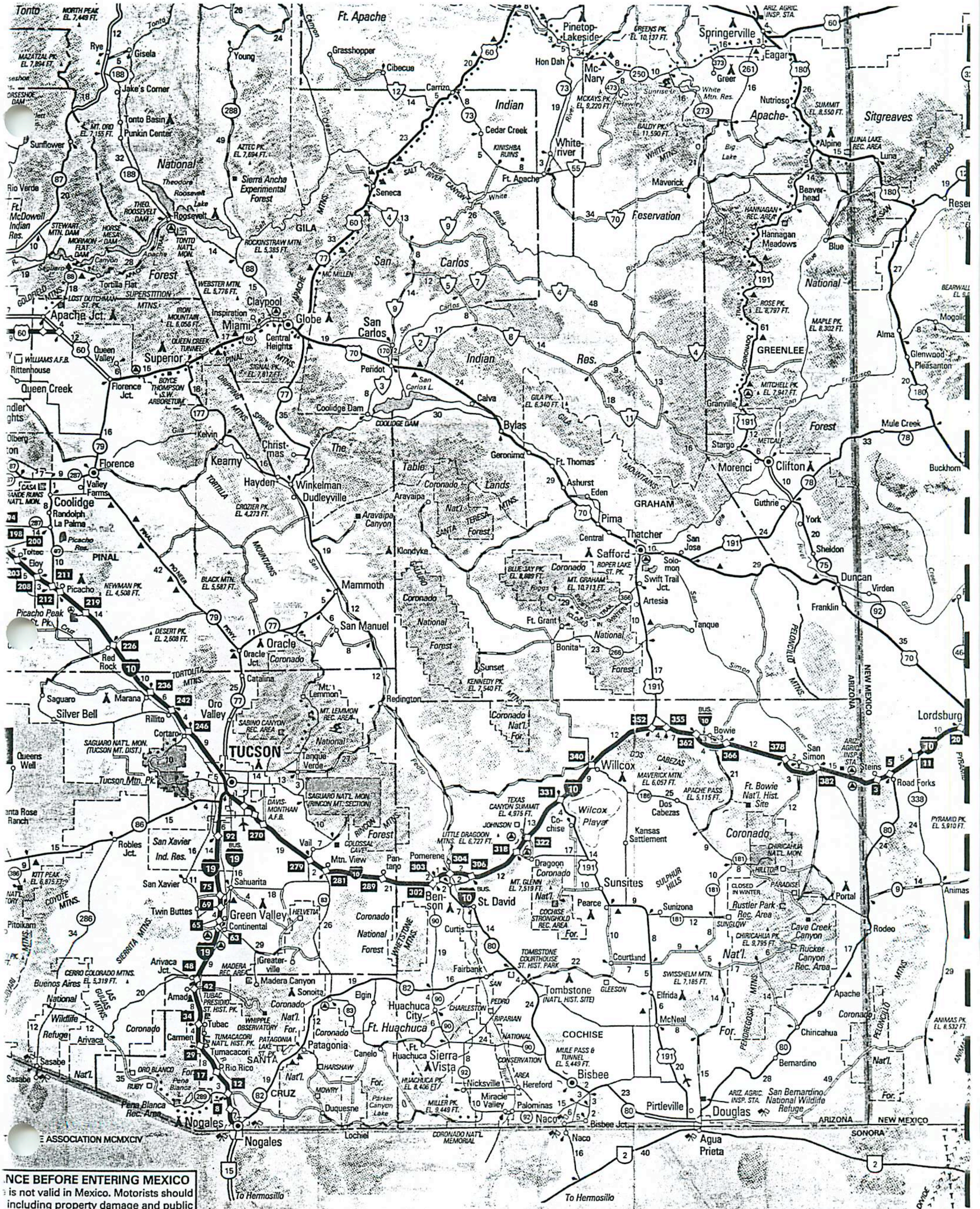
Trip Itinerary

Thursday, 10 Apr 1997	7:00 a.m.	Meet at LPL loading dock
	8:00	Depart LPL; head east on Interstate 10 (Turtle)
	1:30 MDT	Stop for lunch, Las Cruces, NM (Lanagan)
	2:30 p.m.	End lunch; continue on I-10 to El Paso, then east on US 180 / 62
	5:30	Stop at Guadalupe Mountains National Park (Rivkin)
	6:00	Stop at New Mexico state line outcrop
	7:00	Make camp (near Carlsbad Caverns) (Lorenz)
Friday, 11 Apr	8:00 a.m.	Breakfast talk about Carlsbad Caverns (Cohen)
	8:30	Leave camp, drive to Slaughter Canyon
	9:00	Tour Slaughter Canyon Cave, Carlsbad Caverns National Park
	12:00	Lunch (at Carlsbad Caverns visitor center)
	1:30 p.m.	Leave Carlsbad; take US 285 north to Roswell, then US 70 west
	5:00	Arrive at Carrizozo lava field (Keszthelyi, Spitale)
	6:00	Make camp (Valley of Fires park) (I. McEwen)
Saturday, 12 Apr	8:00 a.m.	Leave camp; take US 54 south to Alamogordo
	9:30	Explore White Sands National Monument (Trilling)
	11:30	Lunch (at White Sands)
	12:30 p.m.	Leave White Sands; continue southwest on US 70
	1:00	Stop at Jornada Experimental Range (Haney)
	2:45	Meet guide (Hoffer) at Anthony City Park (S. of Las Cruces)
	3:30	Stop at Kilbourne Hole (Phillips, Chabot, Righter)
	6:30	Make camp (Pancho Villa State Park)
Sunday, 13 Apr	9:00 a.m.	Leave camp; take NM Hwy. 9 W
	11:00 MST	Arrive at Chiricahua National Monument (Grier, A. McEwen)
	1:00 p.m.	Leave Chiricahuas; take AZ Hwy. 186 west to I-10
	2:00	Willcox Playa (optional stop)
	4:00	Return to Tucson

NOTE: Except for beginning and end of trip, times are given in **Mountain Daylight Time**.

Names in parentheses indicate people who will give talks.

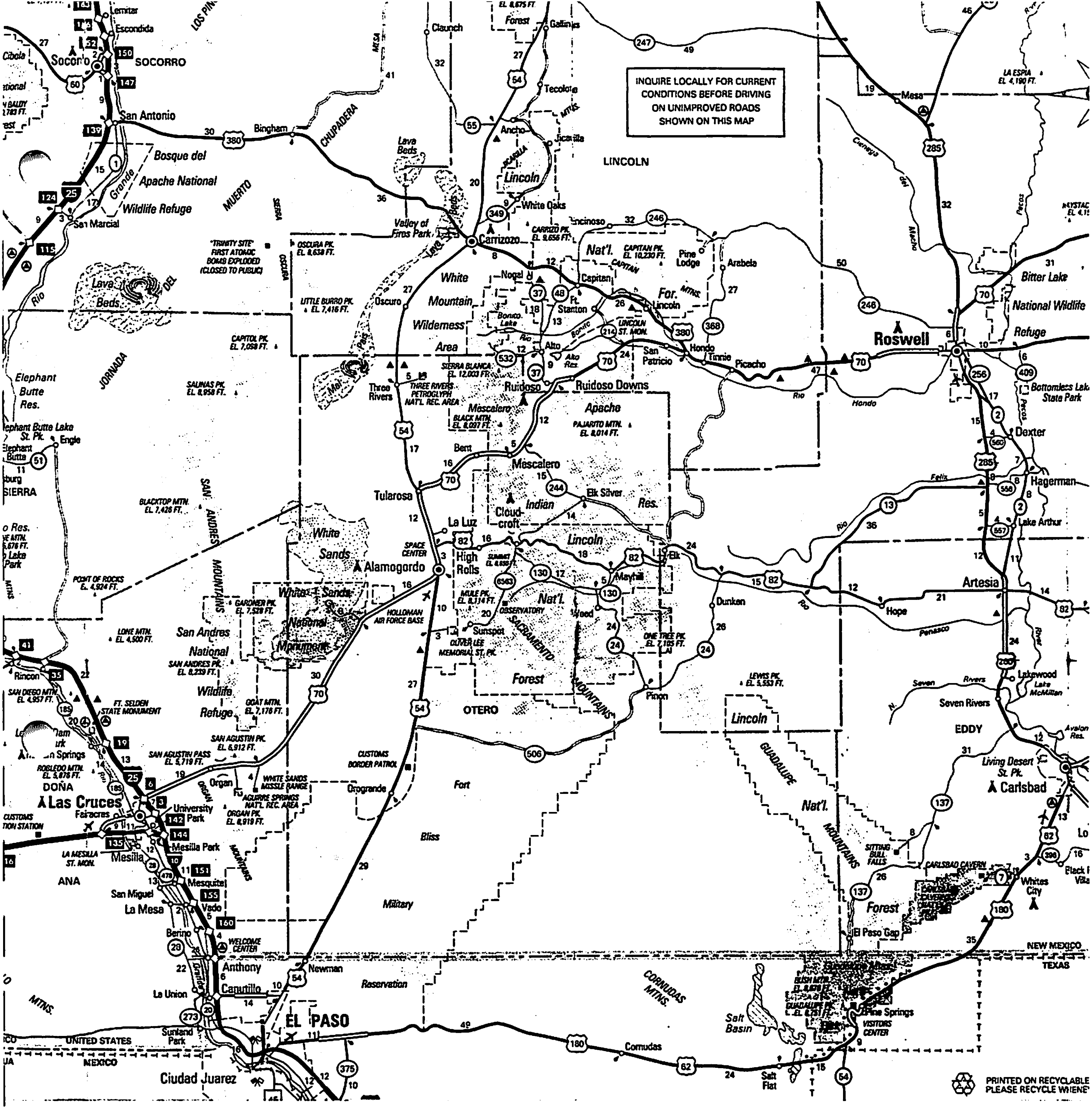
Primary drivers: Will Grundy, Laszlo Keszthelyi, Cynthia Phillips, Kevin Righter.



...NCE BEFORE ENTERING MEXICO

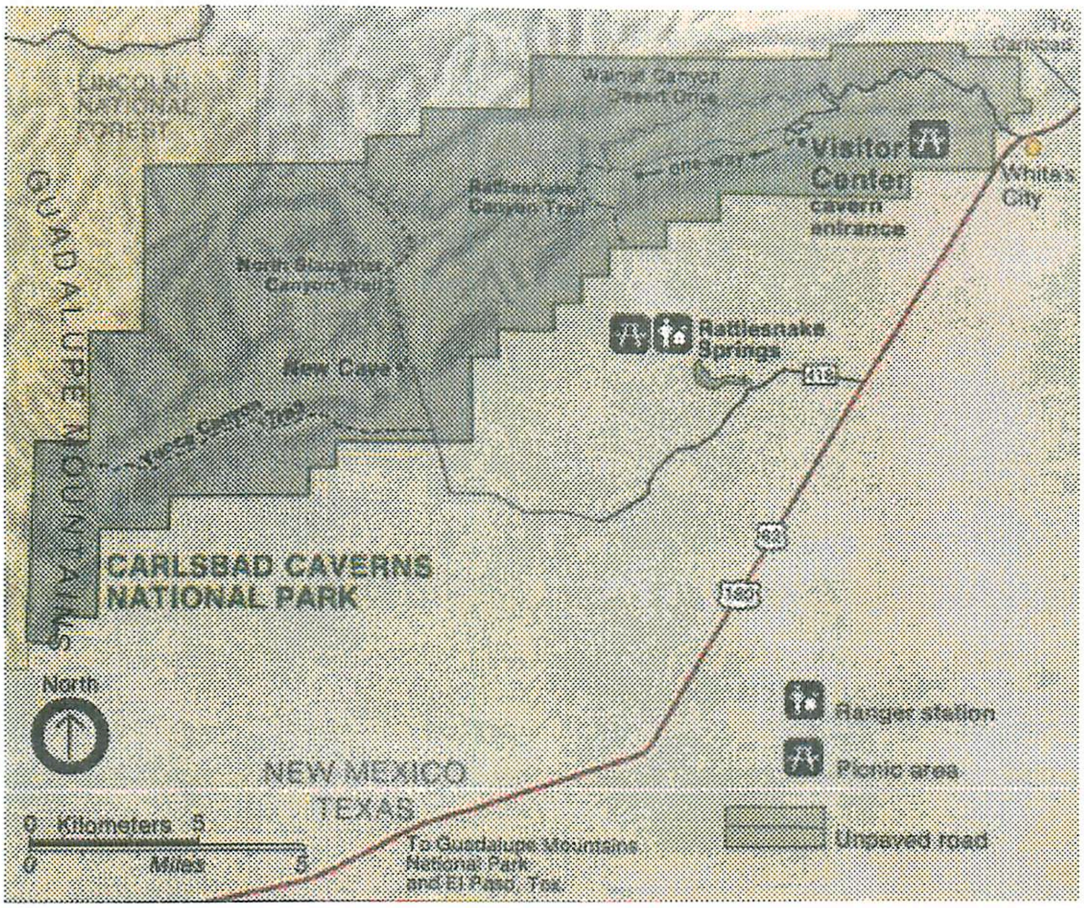
...is not valid in Mexico. Motorists should ... including property damage and public ... Mexican insurance company that has ...s in cities throughout Mexico. The Mexi... minimum requirement for insurance; ... suiting your needs. Make sure you read ...he policy carefully to discern what is and ...utomobile insurance is available at AAA

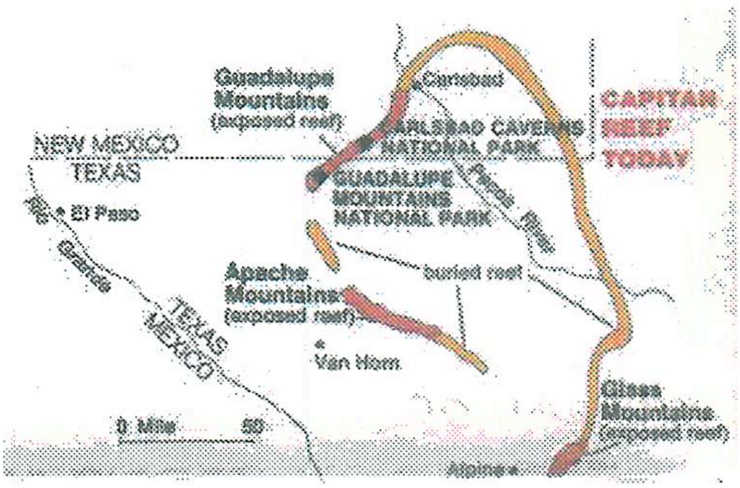
ARIZONA

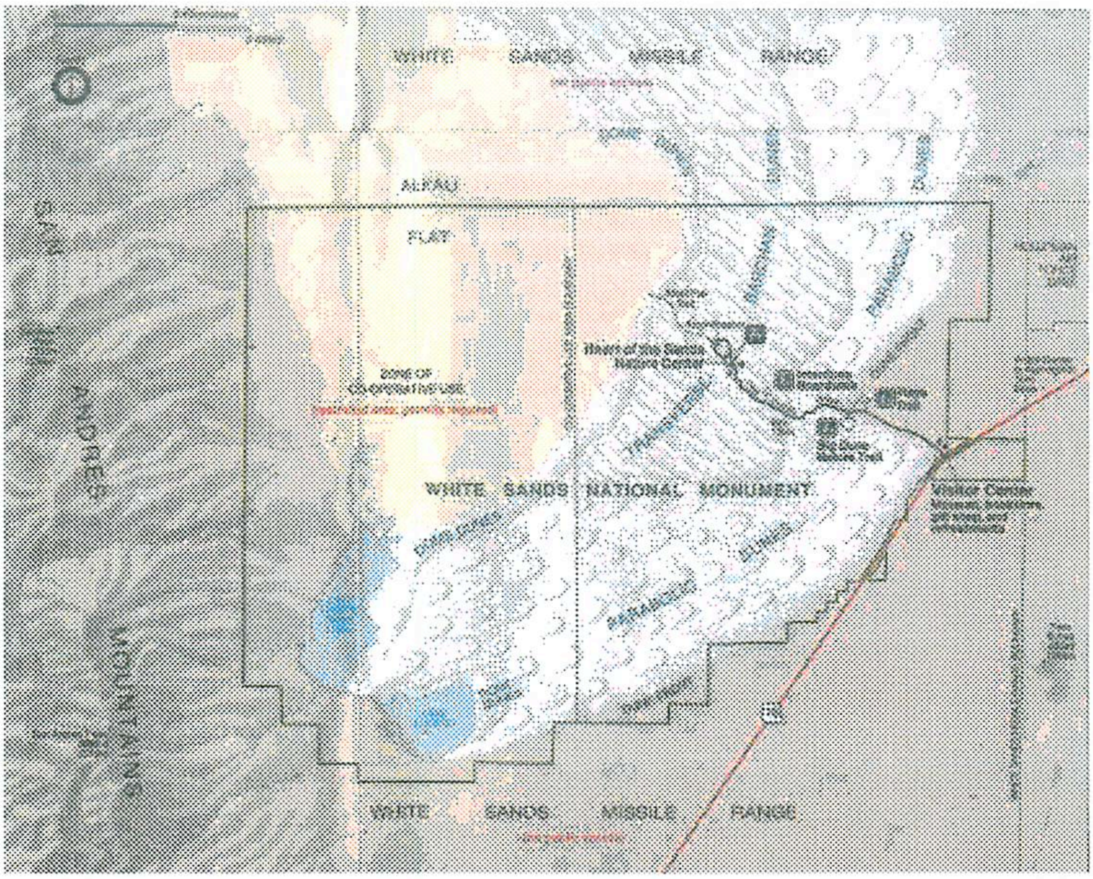


INQUIRE LOCALLY FOR CURRENT CONDITIONS BEFORE DRIVING ON UNIMPROVED ROADS SHOWN ON THIS MAP
SOCORRO
Socorro
San Antonio
Bingham
Bosque del Apache National Wildlife Refuge
San Marcial
Carrizozo
Valley of Fires Park
LINCOLN
Lincoln Nat'l. For.
Capitan
White Oaks
Ancho
Tecolote
Claunch
Gallinas
"TRINITY SITE" FIRST ATOMIC BOMB EXPLODED (CLOSED TO PUBLIC)
White Mountain Wilderness Area
Ruidoso
Ruidoso Downs
Alto
Hondo
Tinnie
Picacho
San Patricio
Roswell
Bitter Lake National Wildlife Refuge
Bottomless Lakes State Park
Dexter
Hagerman
Lake Arthur
Artesia
Hope
Three Rivers
Mescalero
Mescalero Apache Indian Res.
Tularosa
La Luz
Alamogordo
High Rolls
Cloudcroft
Mayhill
Elk
Dunken
White Sands National Monument
San Andres National Wildlife Refuge
HOLLOMAN AIR FORCE BASE
Oliver Lee Memorial St. Pk.
Sunspot
Weed
Pinon
Lincoln Nat'l. Forest
OTERO
EDDY
Lakewood
Seven Rivers
Carlsbad
Living Desert St. Pk.
Whites City
Carlsbad Caverns
El Paso Gap
Guadalupe Mountains
Fort Bliss Military Reservation
Orogrande
Elephant Butte Res.
Engle
SIERRA
Las Cruces
DOÑA ANA
Mesilla
Mesilla Park
University Park
Fairacres
Mesquite
San Miguel
La Mesa
Vado
Berino
Anthony
Chamberino
La Union
Sunland Park
EL PASO
Newman
Ciudad Juarez
UNITED STATES
MEXICO
NEW MEXICO
TEXAS
Cornudas
Salt Basin
Salt Flat
Pine Springs
PRINTED ON RECYCLABLE PAPER PLEASE RECYCLE WHENEVER POSSIBLE

NEW MEXICO


To Carlsbad
Lincoln National Forest
Walnut Canyon Desert Drive
one way
Visitor Center
cavern entrance
White's City
Rattlesnake Canyon Trail
North Slaughter Canyon Trail
Rattlesnake Springs
New Cave
Yucca Canyon Trail
GUADALUPE MOUNTAINS
CARLSBAD CAVERNS NATIONAL PARK
62
180
North
Ranger station
Picnic area
Unpaved road
NEW MEXICO
TEXAS
0 Kilometers 5
0 Miles 5
To Guadalupe Mountains National Park and El Paso, Tex.

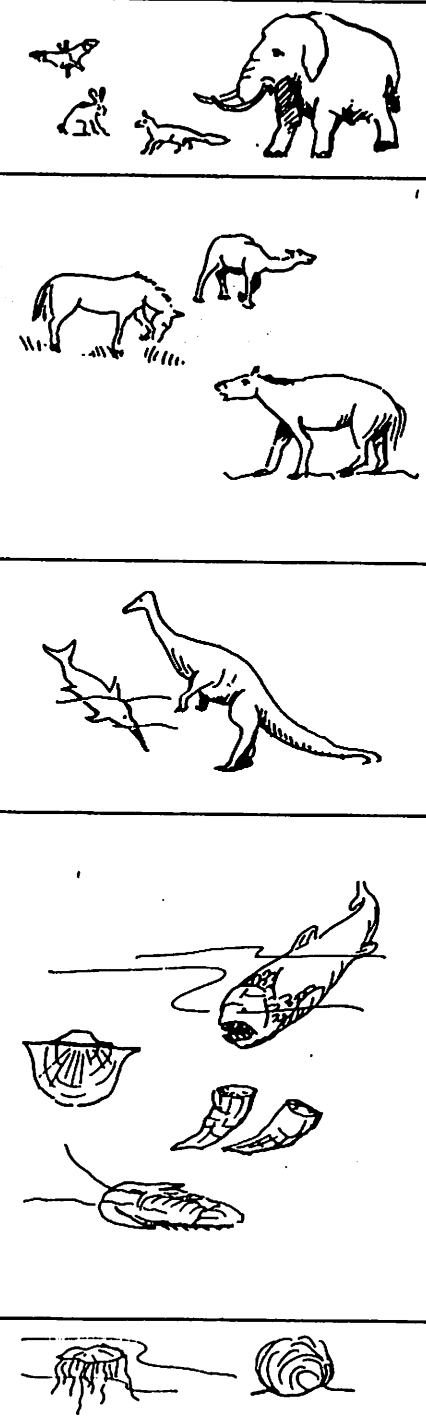

Carlsbad
Guadalupe Mountains (exposed reef)
CARLSBAD CAVERNS NATIONAL PARK
CAPITAN REEF TODAY
NEW MEXICO
TEXAS
GUADALUPE MOUNTAINS NATIONAL PARK
El Paso
Pecos River
buried reef
Apache Mountains (exposed reef)
Van Horn
TEXAS
MEXICO
Glass Mountains (exposed reef)
0 Mile 50
Alpine



WHITE SANDS MISSILE RANGE
ALKALI
FLAT
ZONE OF
COOPERATIVE USE
Heart of the Sands
Nature Center
Visitor Center
WHITE SANDS NATIONAL MONUMENT
SAN
ANDRES
MOUNTAINS
WHITE SANDS MISSILE RANGE

ERA	PERIOD	EPOCH	AGE	EVENTS IN NEW MEXICO
CENOZOIC Age of Mammals	QUATERNARY *Q*	recent	.01	Present erosion cycle trenches Pleistocene deposits, partly refills Rio Grande Rift valley. Basalt eruptions build cinder cones and lava flows near Grants, Carrizozo, and Capulin.
		Pleistocene	2	Cyclic erosion, product of repeated glacial cycles farther north, alternately trenches and fills the Rio Grande Valley. Small mountain glaciers develop in northern New Mexico mountains. Jemez volcano erupts and collapses.
	TERTIARY *T*	Pliocene	5	Basins between ranges fill with debris eroded from surrounding mountains. Some drainage integrates: the Rio Grande becomes a through-flowing stream.
		Miocene	24	Increasing crustal tension creates basins and ranges of southern New Mexico. Intense volcanism builds and destroys many large volcanoes in the southwest part of the state.
		Oligocene	37	The Rio Grande Rift begins to sink between two sets of faults. West of the still-sinking San Juan Basin, plateaus develop.
		Eocene	58	Debris from the Rocky Mountains fill in the San Juan Basin. Mammals diversify, many the ancestors of modern forms.
		Paleocene	66	Continued rise of Rocky Mountains and initial sinking of San Juan Basin accompanies westward drift of continent. Mammals flourish on land. Mineral-bearing intrusions form in parts of the state.
MESOZOIC Age of Reptiles	CRETACEOUS *K*		144	North America breaks away from Europe and starts to drift westward. Briefly, a vast sea covers parts of New Mexico. The Rocky Mountains rise to the north. Finally, a great extinction annihilates many forms of life, ending the Age of Reptiles.
	JURASSIC *J*		208	Seas of sand sweep in wide deserts across northern New Mexico. Dinosaurs roam river floodplains and near-shore marshes.
	TRIASSIC *T̄R*		245	Coastal plain, floodplain, and delta deposits spread across state, their sediments derived from ancestral Rockies. Explosive volcanism adds volcanic ash to these sediments. Dinosaurs appear.
PALEOZOIC Age of Fishes	PERMIAN *P*		286	Southern seas advance across much of New Mexico. A large barrier reef develops in the south, followed by drying up of the sea and creation of extensive salt and gypsum deposits. Locally, erosion removes some earlier sedimentary layers.
	PENNSYLVANIAN *TP*		330	A southern sea covers much of New Mexico with sand, mud, and limestone. With the rise of the ancestral Rockies, sediments become coarser.
	MISSISSIPPIAN *M*		360	Widespread deposition of fossil-bearing marine limestone is followed by uplift and development of karst topography with solution caverns and sinks.
	DEVONIAN *D*		408	Marine deposits—limestone and shale—form in shallow seas.
	SILURIAN *S*		438	Marine deposits form. Most are later eroded away.
	ORDOVICIAN *O*		505	Marine deposits—limestone and shale—form in shallow seas. The first fishes appear.
	CAMBRIAN *C*		570	A western sea advances across the stripped Precambrian surface, depositing sandstone, shale and limestone. Shellfish are widespread and abundant: the Age of Fishes has begun.
PRECAMBRIAN *pC*				Episodes of mountain-building and volcanism alternate with periods of marine and non-marine sedimentation. Intrusions of granite occurred roughly 1.35 billion years ago. Finally, a long period of erosion flattens the landscape.

DOMINANT LIFE FORMS



Geologic calendar

Roadside Geology of New Mexico, H. Chro[nic] 1987

Brief outline of Geologic history of New Mexico

Zibi Turtle

Precambrian (4600-570 Ma)

What is now New Mexico was at the margin of the proto-North-American continent. The geologic record records deposition of sediments and volcanics followed by tectonic deformation and metamorphism. Precambrian granite intrusions date from as much as 1.8Ga in northern New Mexico to as little as 1Ga in the southern part of the state/ and the intrusion of granites (between 1 and 1.8Ga)

Paleozoic (570-240 Ma)

Most of state was covered by shallow seas which underwent a number of transgressions and regressions throughout the era. This resulted in the deposition of thick sequences of limestones, sandstones, and shales. Towards the end of the era, when the continents were coming together to form Pangaea, uplift pushed the shoreline southward and a large (>100km) reef grew in what is now southeastern New Mexico. This reef is preserved in the Guadalupe Mountains. As the sea continued to retreat, salt and potash were deposited by the evaporating marine waters.

Mesozoic (240-65 Ma)

Most deposits from the Jurassic and Triassic periods were sediments laid down by rivers flowing westward across the continental plain to the ocean. In the Cretaceous period New Mexico was on the western shoreline of a shallow ocean that was covering most of central North America. The shoreline transgressed and regressed across New Mexico a number of times and the plants that lived in swampy areas along it formed coal deposits in the northwestern and northeastern parts of the state. The Laramide orogeny responsible for the uplift of the San Juan Mountains in southwestern Colorado resulted in the deposition of large amounts of clastic sediments in the San Juan basin.

Cenozoic (65 Ma - present)

Localized volcanic activity continues into the Tertiary. Then, volcanism in southwestern and central New Mexico intensifies greatly as the North American plate overrides the Farallon plate. Thick ash-flow tuffs, andesite, rhyolite, and basalt flows emanate from volcanic cauldrons up to 50km in diameter. (Some of these cauldrons now form the cores of the Mogollon-Datil plateau, the Black Range, and the Organ, Magdalena, San Mateo, and Peloncillo mountains in southwestern New Mexico.) Hydrothermal activity associated with the volcanism led to the formation of ore deposits.

- 30Ma ago extension leads to the opening of the Rio Grande rift.
- ~20Ma ago extension creates basin and range terrain.

Recent volcanic events in New Mexico:

•10 - 1.4 Ma -- Volcanism in Jemez mountains. First basaltic and rhyolitic flows are extruded. Then at ~1.4Ma explosive eruptions create ash-flow tuffs and pumice. And finally, the magma chamber collapsed forming the 22km diameter Valles Caldera.

•8 Ma - 4.5ka -- Volcanism in northeastern New Mexico creates numerous cones and lava flows.

•3.5-2Ma -- Taylor volcanic field in west-central New Mexico active.

•1.5Ma-~present -- Zuni-Bandera volcanic field active.

500-1000A.D. -- Carrizozo flow

1300A.D. -- McCarty's flow

•<1Ma -- Volcanism southwest of Las Cruces.

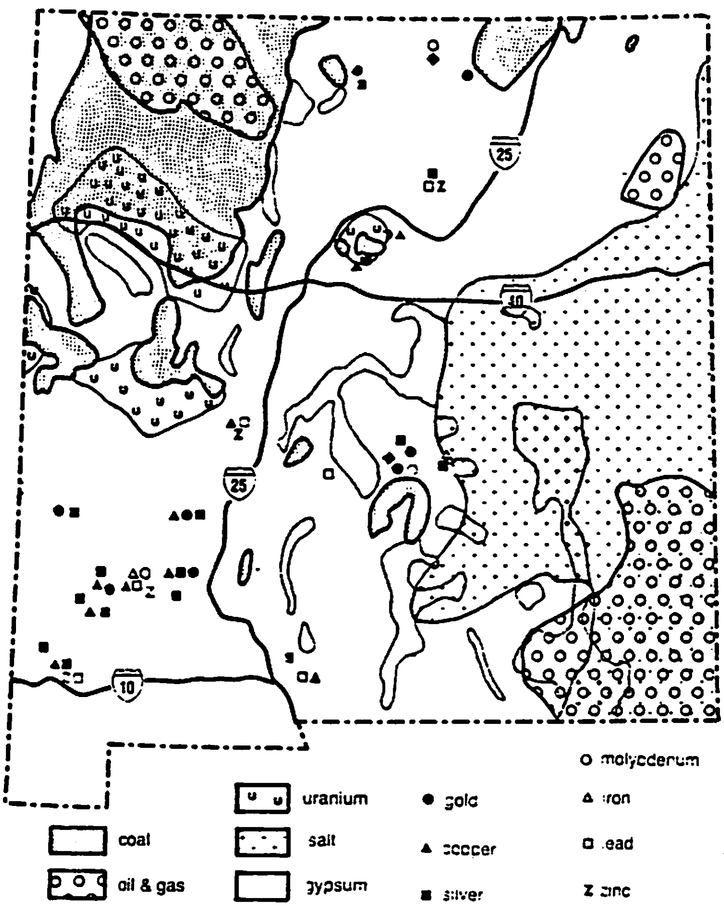
•150-200ka --Volcanism near Albuquerque.

References:

Chronic, H., Roadside Geology of New Mexico. Mountain Press Publishing Co. Missoula, 1987.

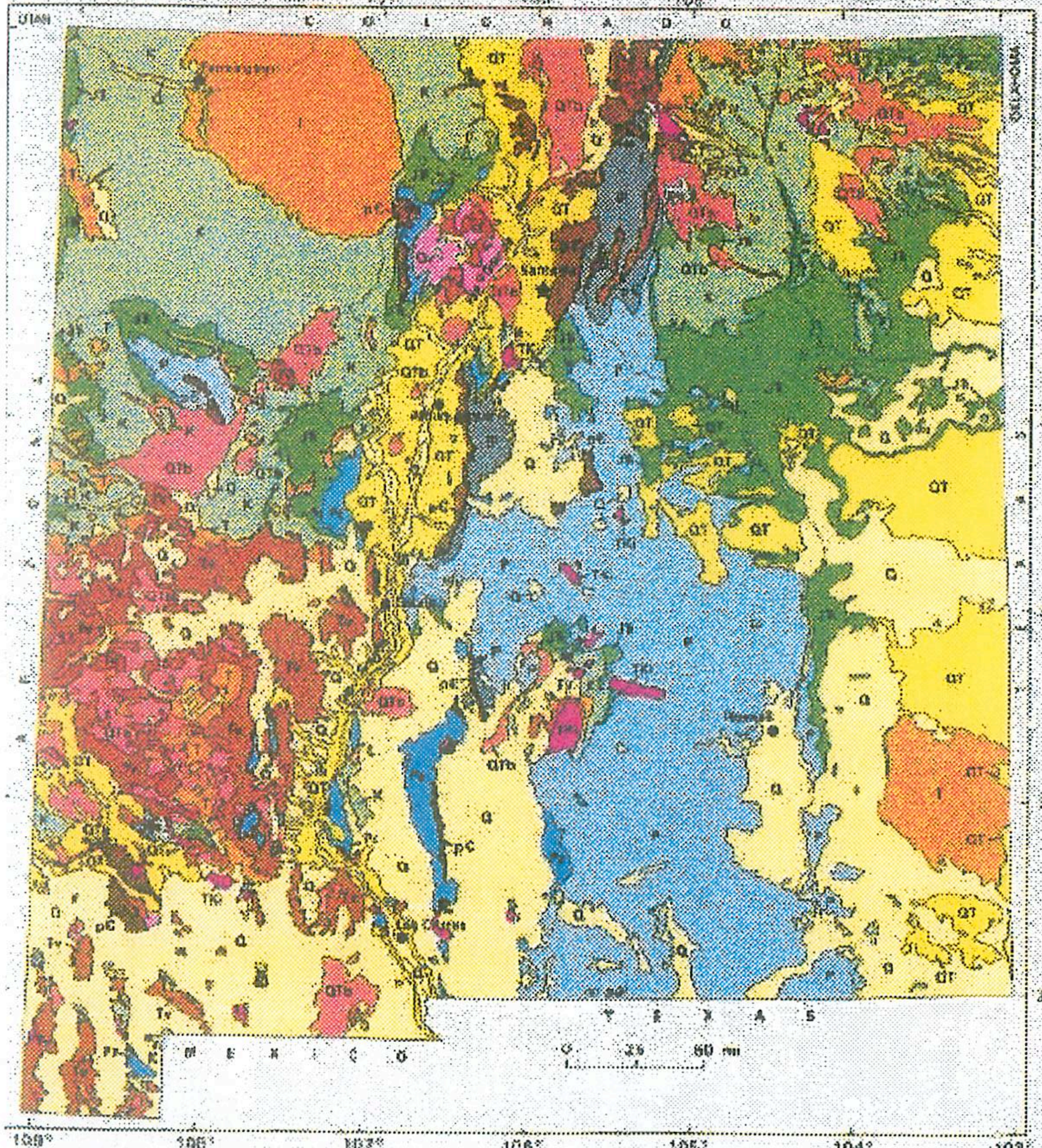
Petersen, M.S., Rigby, J.K., and Hintze, L.F., Historical Geology of North America. Wm. C. Brown Co. Pub., Dubuque, 1974?

Williams, J.L., Ed., New Mexico in Maps., Univ. of New Mexico Press, Albuquerque, 1986.



New Mexico Bureau of Mines and Mineral Resources
A DIVISION OF
New Mexico Institute of Mining & Technology

Socorro, New Mexico 87801



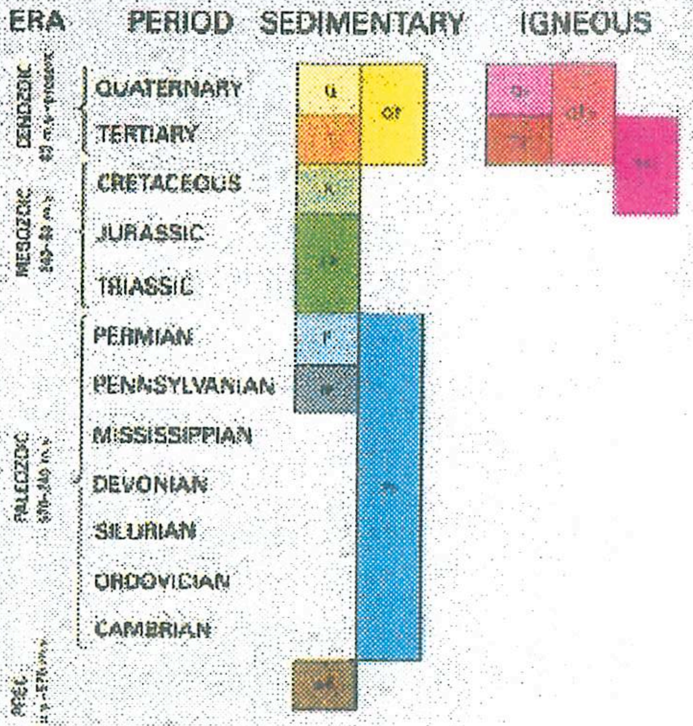
Geology by Robert M. North

Drafting by Teresa Mueller and Debbie Vetterman

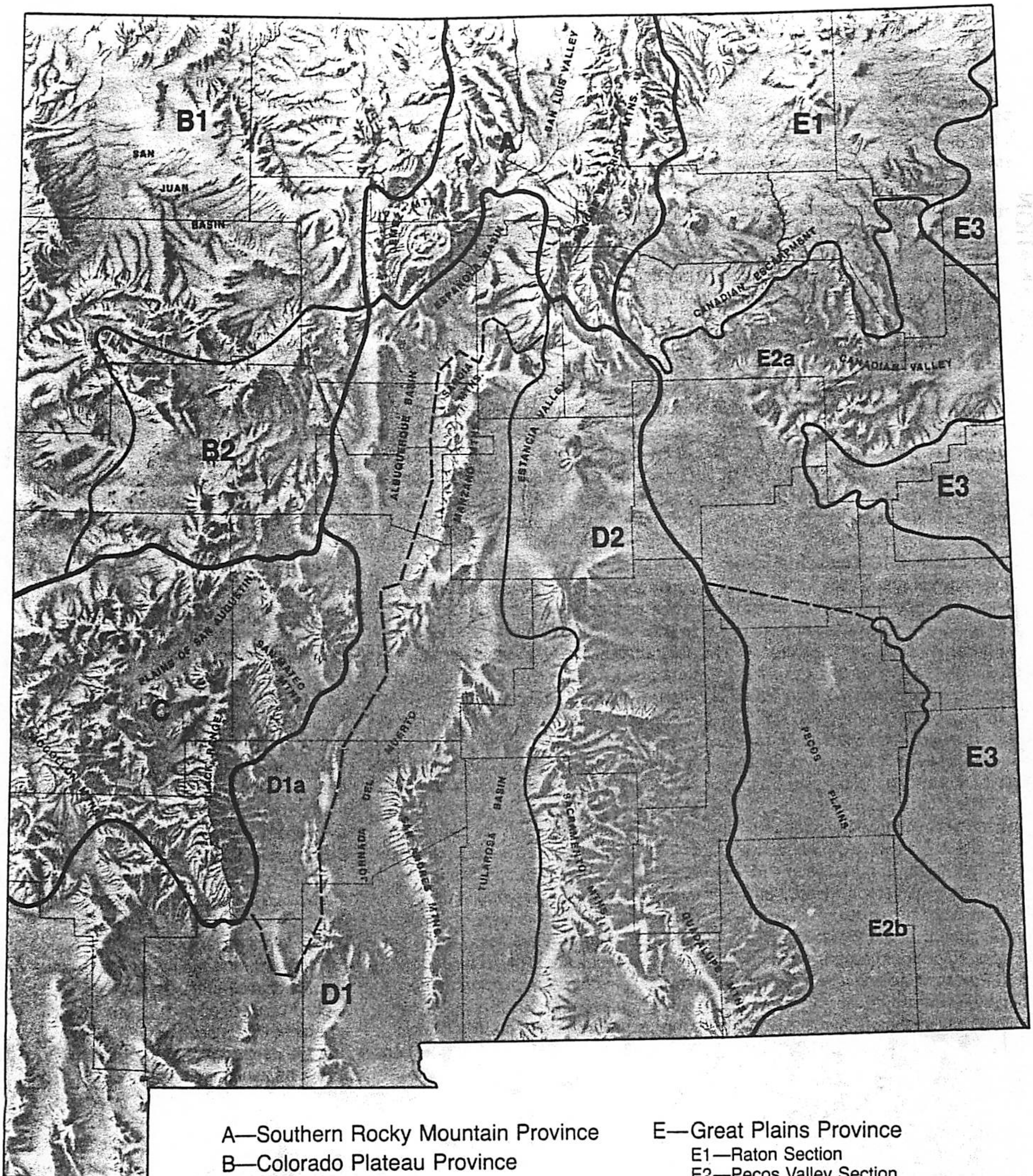
Generalized geologic map of New Mexico

1984

EXPLANATION



- Q — Quaternary sediments
- QT — Quaternary–Tertiary sediments
- Qr — Quaternary rhyolites and tuffs
- QTb — Quaternary–Tertiary basalts and andesites
- T — Tertiary sediments
- Tv — Tertiary volcanics
- TKi — Tertiary–Cretaceous intrusives
- K — Cretaceous sediments
- TR — Jurassic–Triassic
- P — Permian
- IP — Pennsylvanian
- Pz — Paleozoic undifferentiated
- pC — Precambrian



A—Southern Rocky Mountain Province

B—Colorado Plateau Province
- B1—Navajo Section
- B2—Acoma-Zuni Section

C—Datil-Mogollon Section

D—Basin and Range Province
- D1—Mexican Highland Section
  - D1a—Rio Grande Subsection
- D2—Sacramento Section

E—Great Plains Province
- E1—Raton Section
- E2—Pecos Valley Section
  - E2a—Upper Pecos Valley Subsection
  - E2b—Lower Pecos Valley Subsection
- E3—Llano Estacado

Shaded relief courtesy of N.M. Bureau of Mines and Mineral Resources.

0 10 20 30 40 50 Miles

The Rio Grande Rift
(No awards for title creativity expected)

Peter Lanagan

An Abbreviated History

A regional extension event 32-27 mya reactivated a north-trending zone of weakness in the southern Rocky Mountains. The existence and orientation of this zone of weakness was due to late Paleozoic and late Cretaceous/early Tertiary orogenies. 26 mya, the crust along the rift had sagged to form broad basins. Over time, these basins were filled by mafic lava flows, volcanic ash beds, and alluvial fill. As the rift widened, more basins formed along lineaments sub-parallel to the rift.

The Rio Grande Rift is divided into three distinct regions.

Northern Section: Leadville CO to Alamosa CO

Rifting in this region initiated about 27 mya. The graben system in this region tapers northward and pinches out 20 kilometers north of Leadville. However, extensional processes, as indicated by a broad zone of block faulting, continues northward to near the Wyoming border. Compared to the rest of the Rio Grande Rift, there was little volcanism associated with the axial basins.

Central Section: Alamosa CO to Socorro NM

With the exception of the area around Taos, there was little early rift volcanism in this region. However, late-rift volcanism was significant in this region.

Southern Section: Socorro NM to El Paso TX

This section of the rift is difficult to distinguish from the surrounding Basin and Range Province based on physiographic interpretations alone. Unlike the northern and central sections which are dominated by large, single basins, the southern section of the rift is composed of a series of subparallel, broad basins. Rifting in this section began 32 mya, and, with the exception of a latent period 20-13 mya, both early-rift and late-rift magmatism has been noted in this region.

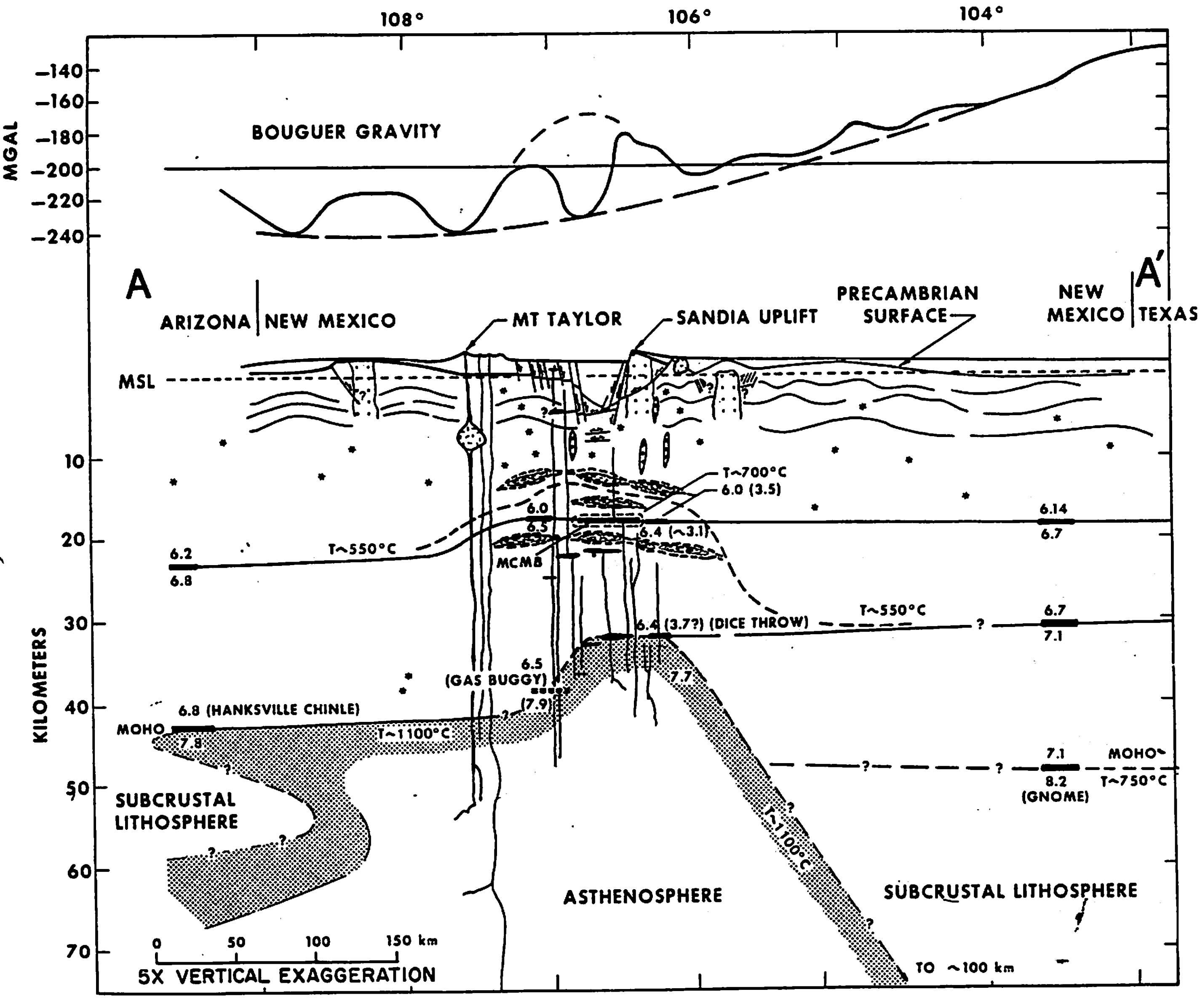


FIGURE 2. Cross section through northern Albuquerque–Belen Basin. See Figure 1 for location. Locations of intracrustal boundaries, interpreted from travel times, and record-sections of correlated phases are plotted as short, heavy lines at the longitudes where seismic profiles intersect the cross section. Numbers are P-wave velocities in km/s (numbers in parentheses are S-wave velocities). Profiles are identified by locations of the shotpoints (Chinle–Hanksville: Roller, 1965) or by code names of the main source explosions (DICE THROW: Olsen and others, 1979; GASBUGGY: Toppozada and Sanford, 1976; GNOME: Stewart and Pakiser, 1962). The Chinle, GASBUGGY, and GNOME profiles were obtained at a relatively early stage of U.S. crustal-profiling efforts, when station spacing was relatively coarse (10–50 km) and true amplitude/waveform data were inadequate to permit more than estimates of possible velocity gradients or fine structure in the principal crustal layers. DICE THROW average station spacing was about 3 km, allowing better gradient estimates using modern synthetic seismogram-modeling techniques. Generalized distribution of earthquake hypocenters in the upper crustal layer is shown by asterisks, as are the specific deep crustal events of 1976/1977 (Sanford and others, 1979). A Bouguer gravity-anomaly profile at the latitude of the cross section is shown at the top (Cordell and others, 1982). The midcrustal magma body (MCMB) at Socorro has been projected into the cross section. Locations of basaltic dikes, though schematic, are based partly on heat-flow data (e.g., Clarkson and Reiter, this guidebook). Lensoidal "megaboudins" in the middle crust represent region of discontinuous ductile flow (see text).

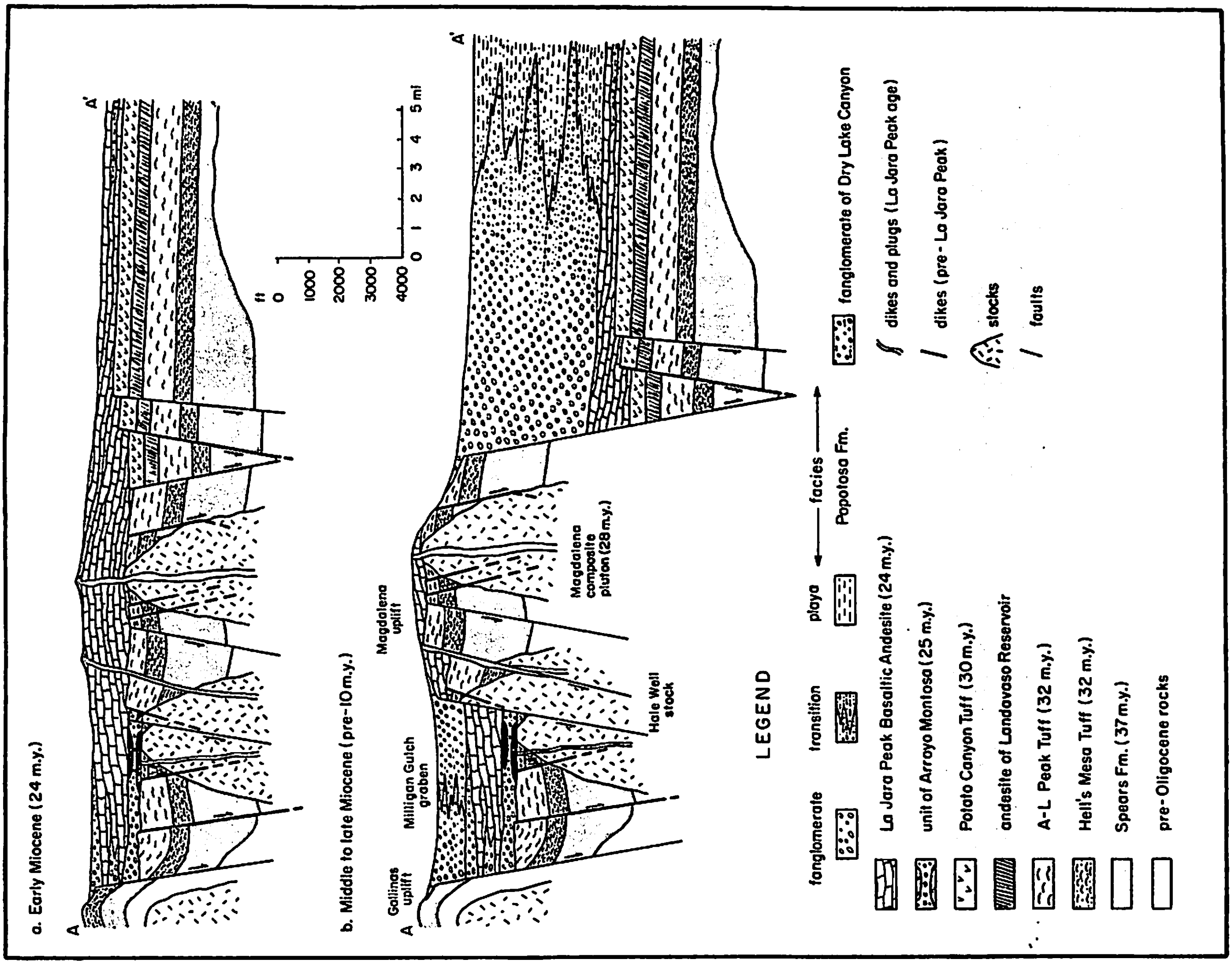
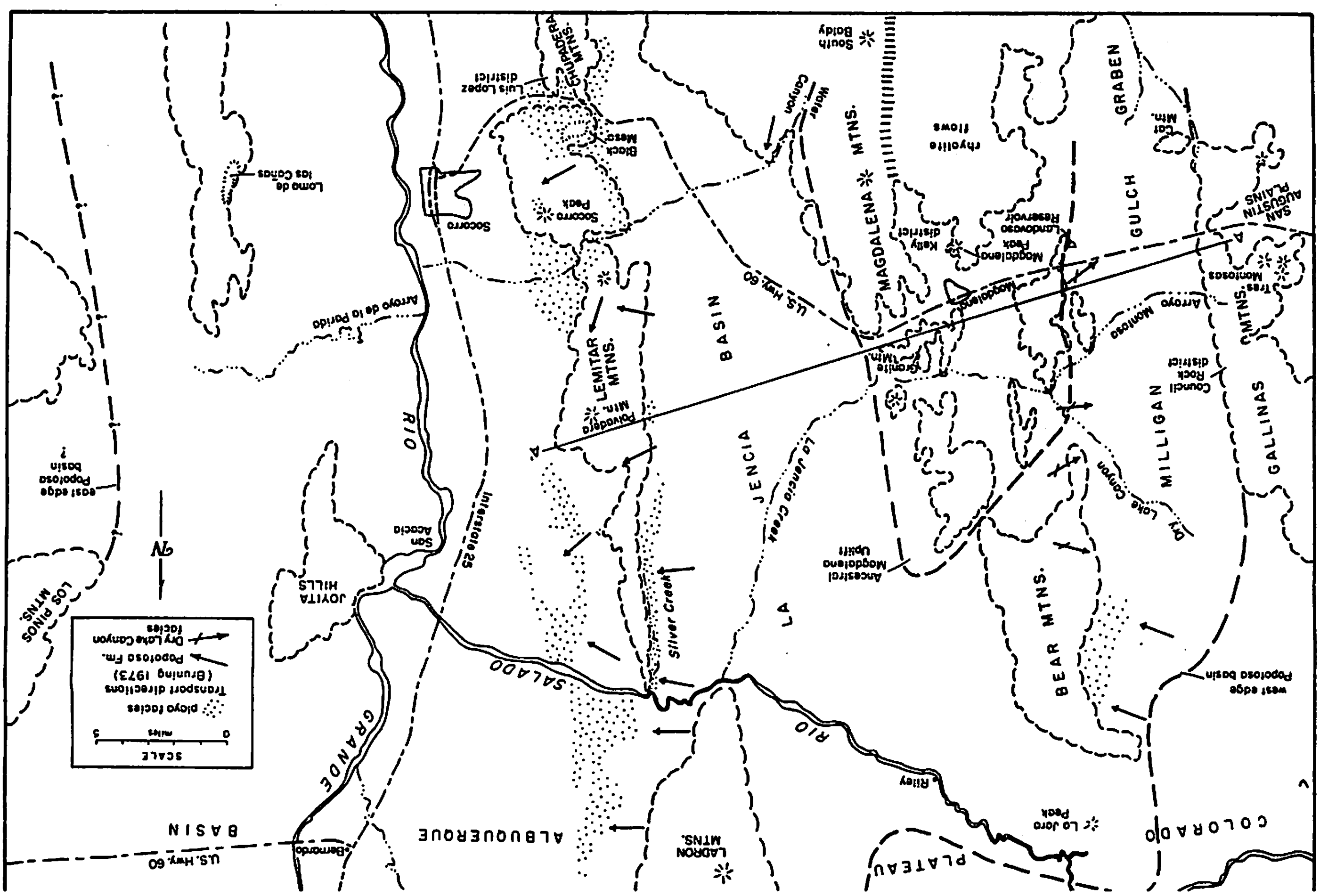
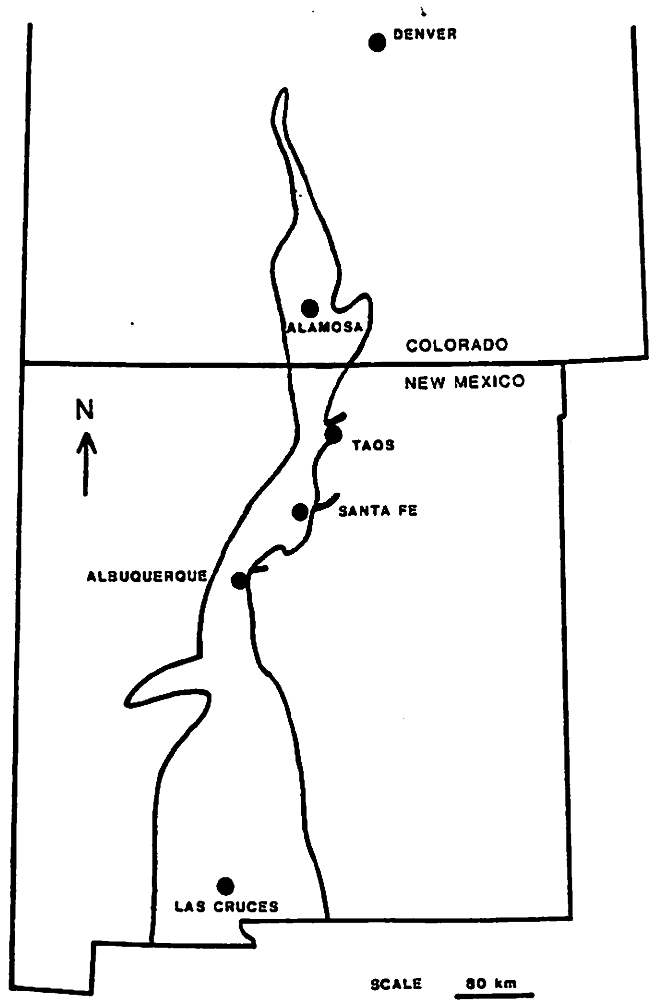


Figure 3. Schematic cross-sections of the Popotosa basin from the Gallinas Range to the present Lemitar Range (not shown). The approximate line of section (A-A') is shown on Figure 5.



The Rio Grande Rift



Extent of rift in bold.

References

Baldridge, W. Scott, Kenneth H. Olsen, and Johnathan P. Callender. "Rio Grande Rift: Problems and Perspectives". New Mexico Geological Society Guidebook, 35th Field Conference, Rio Grande Rift: Northern New Mexico. 1984.

Chapin, Charles E. and William R. Seager. "Evolution of the Rio Grande Rift in the Socorro and Las Cruces Areas". New Mexico Geological Society Guidebook, 36th Field Conference, Las Cruces Country. 1975.

Chapin, Cahrles E. "Evolution of the Rio Grande Rift-A Summary". Rio Grande Rift: Tectonics and Magmatism. 1979.

Kelley, Shari A. and Ian J. Duncan. "Tectonic History of the Northern Rio Grnade Rift Derived From Apatite Fission-Track Geochronology". New Mexico Geological Society Guidebook, 35th Field Conference, Rio Grande Rift: Northern New Mexico. 1984.

The Guadalupe Mountains and El Capitan Reef

With your Permian host, Andy Rivkin

The Guadalupe Mountains of Texas are a completely exposed sequence of evaporite, carbonate and sandstone transitions from ancient shelf to marine basin, and the largest fossil reefs in world. Included in this reef is El Capitan cliff, composed entirely of reef limestone and 1000 feet high, made from calcareous sponges and encrusting algae.

The reef formed a horseshoe around the Delaware Basin (an inland sea about the size of Black Sea) in late Permian time (280-230 mya). Meantime, the Appalachian Orogeny was occurring as Africa and North America collided, and volcanoes were forming in Idaho and Nevada on the edge of craton.

Anyhow, at this time Texas/New Mexico were in an arid tropical region south of the Equator. Three different reefy environments were present: 1) the fore reef talus and deeper sea basin inside the Delaware Basin. 2) the reef crest and shallow fore reef of the El Capitan reef complex 3) and a back reef and lagoon in midland basin. Three different rock types (facies) were formed in each environment: 1) produced a dark limestone (dark due to organic material left in a reducing anaerobic environment) 2) produced light massive fossiliferous limestone– as encrusting organisms grew over old skeletal remains and held the whole thing together (c.f. coral, which this is not!) 3) shows a progression from carbonates through evaporites to land-derived rocks.

Fore reef? Encrusting organisms?

Defining our terms:

- **reef:** "submerged resistant mound or ridge formed by the accumulation of plant and animal skeletons...the largest living reefs occur in shallow (not over 425 feet) tropical seas (temperatures over 68 °F)..." (Harris and Tuttle 1990)
- **fore reef:** seaward-facing, high wave action → blocks of living and dead material rolls down slope, forming talus, moving reef outwards
- **reef crest:** top of reef. high light intensity, fosters rapid upward growth of plants and animals that form framework of reef.
- **back reef:** shoreward facing, low wave/current activity, fine sediment is carried back into this area → muddy, stagnant, saline water.

So, as sediment accumulates, animal/plant remains and sediment are compacted, recrystallized, lithified as limestones. Back reef sediment has lots of magnesium → dolomite is formed. Evaporites are formed in especially salty water. Permian reefs have anhydrite, gypsum, halite as salt content increases.

And the planetary connection?

Relax. Look at the following timeline instead!

1. Delaware Basin formed by earliest Permian as inland basin with narrow outlet at open ocean, with an area of about 10,000 square miles and a circulation pattern similar to the Mediterranean. During this time, 1600-2200 feet of limestone and shale were deposited (n.b. in early 1990's, an interpretation of the Delaware Basin as an enclosed sea has re-emerged).

2. During the early mid-Permian, the basin stopped subsiding. Gypsum, dolomitic limestone and sandstone were deposited nearshore, with black thin-bedded limestone laid down in the deepe, stagnant part of basin. Small reefs form in patches along rim of basin.

3. Mid-permian: The basin subsides again, larger patch reefs form, and cherty dolomites and sandstones form in and around basin.

4. During the late mid-permian, the Delaware Basin subsides rapidly (possibly due to compression when North and South America and Africa collide). Reef growth intensifies. Lagoon and back reef facies form, as do the reef crest and offshore basin facies.

5. At the end of mid Permian, the basin stopped subsiding and reached a stable position. The largest reef expanded 350 miles around rim of basin, and started slowly moving toward middle.

6. Upper permian: continued sedimentation (plus drop in sea level?) caused a gradual shallowing and drying up of basin. Extensive accumulations of deep water evaporites covered the lagoon and reef and eventually the basin. Laminae of anhydrite/gypsum, calcite and halite precipitate first. Halite and K-rich salts precipitate nearshore and around basin margin, then all over.

7. Through the end of Permian, land-derived siltstones and sandstones were deposited on top of the evaporites as rivers migrated toward area.

8. During the late Mesozoic/early Cenozoic, tectonism, and major faulting brings the range up, separating the reef from fault blocks to the west.

9. From then to now, mass wasting has been the major driver of change.

Castile Evaporites:

The Castile evaporites contain laminations correlated for over 60 miles, with each lamination measured and assembled into a 200,000 year paloclimatic record with evidence for orbital climatic variations.

The bands we'll be seeing are from seasonal precipication of calcium carbonate and sulfate from evaporating seawater. The thin dark laminae are calcium carbonate and organic matter. Thicker white laminae are gypsum/anhydrite intergrown. Occasional 10 cm or greater bands of gypsum show recrystallization or periods of less calcite precipitation. Because the layers correlate over large distances, the layers were laid down almost instantaneously over basin. This shows the climatic forces responsible were of a scale rather larger than the basin, like seasons! A 100,000 year period in the variation in lamina thickness is seen that is thought to be related to eccentricity changes in the Earth's orbit. There is also a 20,000 year period that correlates to precession of the Earth's pole.

Microfolding can be seen in the layers. These seem to be due to tectonic compression long after deposition/consolidation of the layers. In this way, the thinner layers buckled, thicker ones didn't. Naturally, this is still controversial since in some places thin layers and thick layers remain flat, while middle-sized layers folded...

And the planetary connection?

Right. The Castile evaporites constitute the longest uninterrupted seasonal climatic record that has been found. Well, it's possible that the Greenland ice cores are longer, but as of the time the references I consulted were written, it was the Castile evaporites. Anyhow, the Mars '98 putative mission to the layered polar terrain on Mars is ostensibly going to obtain long-term paleoclimatic data on Mars. The Castile evaporites show in fun, close-to-home, low-fat form how layered deposits in rock can directly relate to the climate. So there.

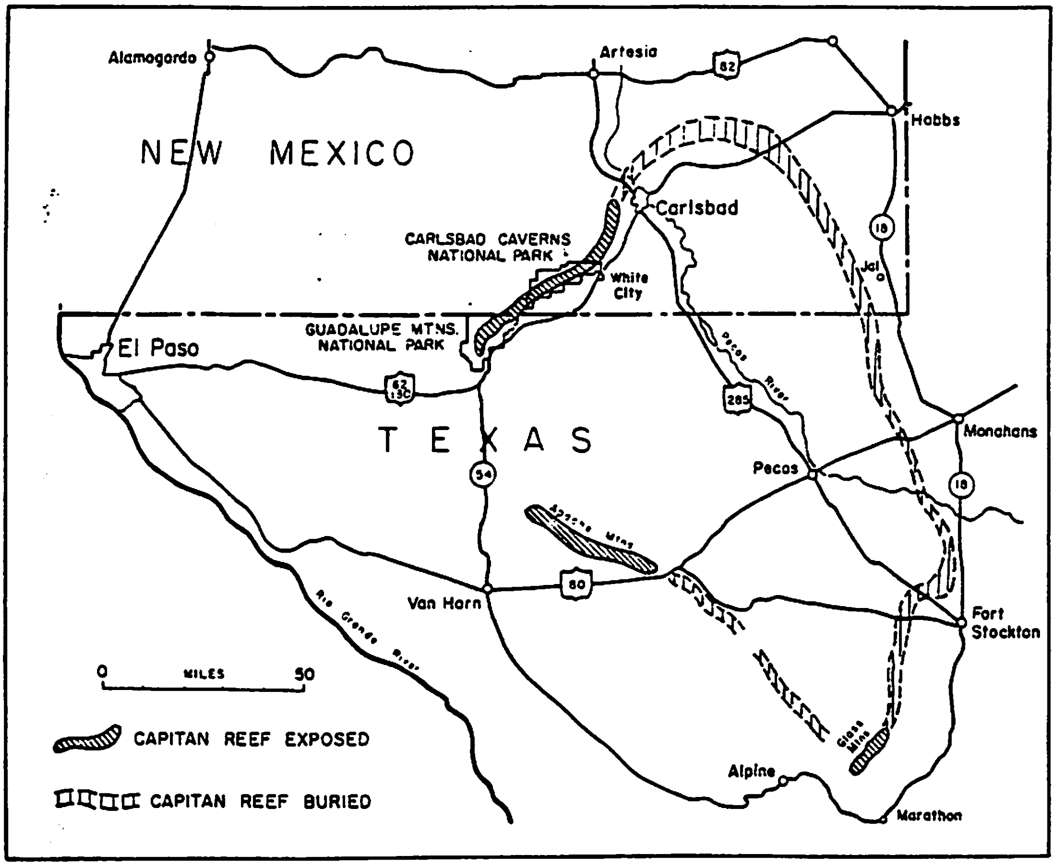


Figure 15.3 Exposed and unexposed parts of the Capitan Reef in Carlsbad Caverns and Guadalupe Mountains National Parks and vicinity. From D. Murphy, *The Guadalupes*. © 1984 Carlsbad Caverns/Guadalupe Mountains Natural History Association. Used by permission.

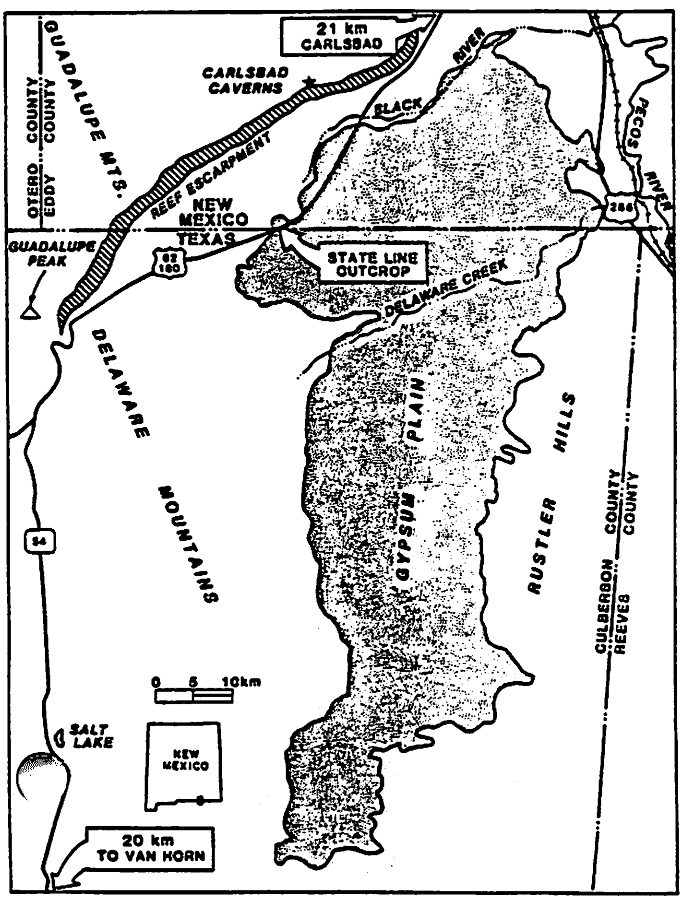


Figure 1. Location of state-line outcrop in relationship to th Gypsum Plain and to other physiographic features in th vicinity.

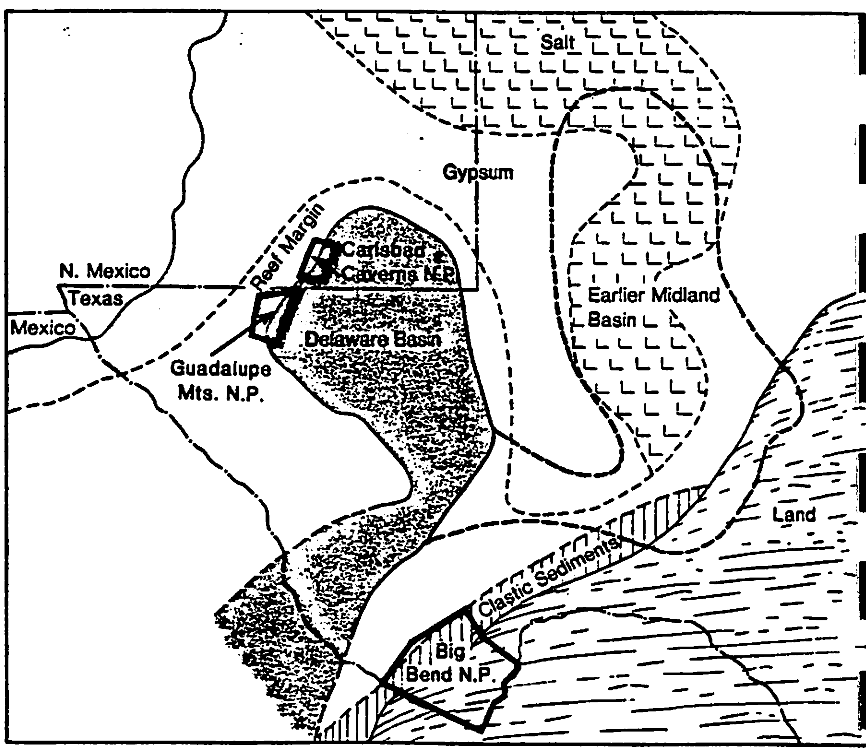


Figure 15.4 Location and extent of the Delaware and Midland Basins in Permian time, superimposed on a modern map of New Mexico and Texas. In Permian time, the region was in the equatorial belt, to the southwest of its present position. Modified from *Historical Geology of North America*, 2nd edition, M. S. Petersen, J. K. Rigby, and L. F. Hintze. © 1973, 1980 Wm. C. Brown Publishers. Used by permission.

Secret Wonder Weapons of New Mexico

Ralph Lorenz

New Mexico has played a role in the development of three items which have been instrumental in shaping the late 20th century, and particularly the way wars are fought. These are nuclear explosives, the ballistic missile, and radar.

The Bomb - Los Alamos/Alamogordo

The Manhattan Project was a mammoth undertaking, eclipsed only by Apollo in scope, and made much harder by the need for secrecy. As well as production facilities for fissile material, a laboratory was needed for the construction of the weapon itself and the theoretical work to design it.

The location of this facility (termed 'Site Y') was dictated by the need for a test site, suitably isolated (more to prevent the scientists mingling with the populace than anything else), with good weather to permit experiments and construction outdoors year-round, plus good transportation and the availability of local labor. An additional factor was Oppenheimer's liking for the desert landscape.

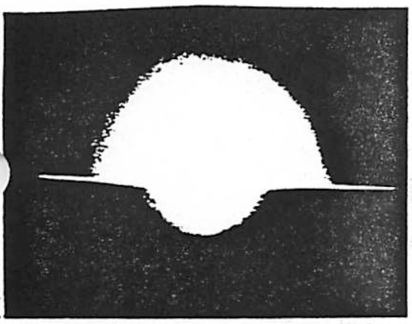
After examining a number of sites, it was decided to buy a boys school near Los Alamos. It had some infrastructure (the $440,000 purchase included 60 horses, 2 tractors, 2 trucks, 50 saddles, 800 cords of firewood, 25 tons of coal and 1600 books) and, being on a mesa, was easy to isolate by fencing and inhibit surveillance. (On the subject of accounting, the Los Alamos facility, operated by the University of California, stipulated in its contract that it would not be liable to reimburse the government for the vaporization of millions of dollars of plutonium.)

The scientists housed there included many non-US scientists as well as Americans, including refugee scientists from Europe. The fencing erected to keep prying visitors away made some of the refugees uncomfortable. The local hazards (particularly at the test site) included rattlesnakes and fireants. The well-water was contaminated with gypsum, which stiffened the hair and acted as a purgative...

The nuclear test itself was performed in 'Jornada del Muerto', an area of flat scrub 60 miles NW of Alamogordo, 210 miles SW of Los Alamos. The test was of a plutonium implosion device (the gun-type Uranium device used on Hiroshima was technically much easier to achieve, and no test was felt necessary.)

The 'Trinity' test occurred at 05:29:45 on July 16, 1945. It required 32 simultaneous detonations to compress a plutonium ball. The ball segments had to be manufactured to such close tolerance that temperature differentials initially prevented the assembly of the device.

Planetary Connection : explosion cratering is of course a well-known analogue for impact cratering. It was calculated that the first atomic test should have been detectable by reflection from the Moon (cf attempts to spot SL-9 impacts)



88–93. The first man-made nuclear explosion: Trinity, 0529:45 hours et seq., July 16, 1945. The sequence runs down this page and up the next. Note change of scale as the fireball expands. "This power of nature which we had first understood it to be," said I. I. Rabi. "—well, there it was."

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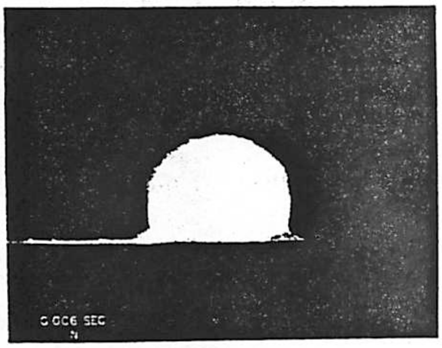

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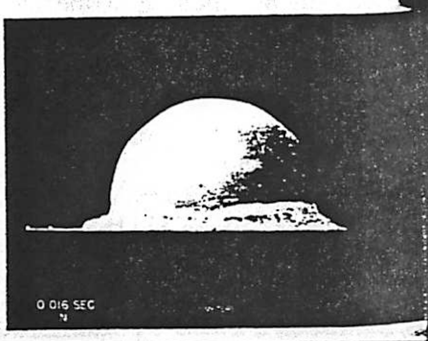

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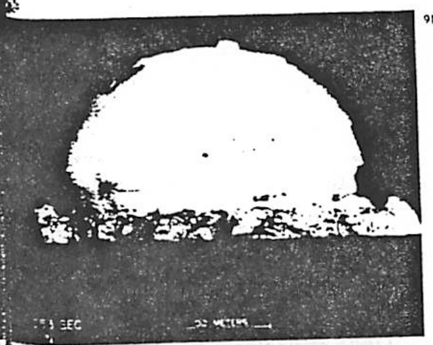

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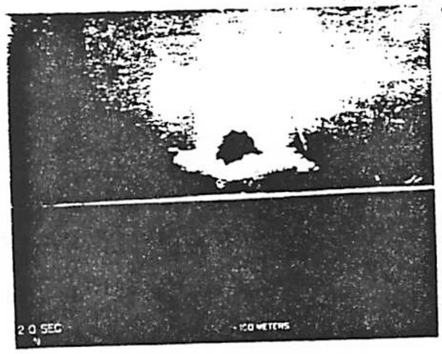

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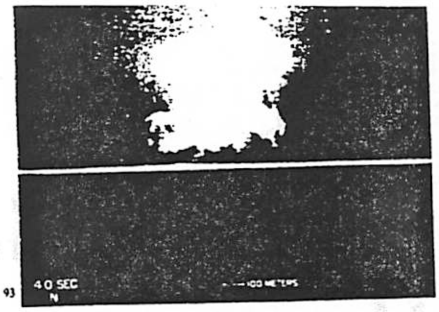

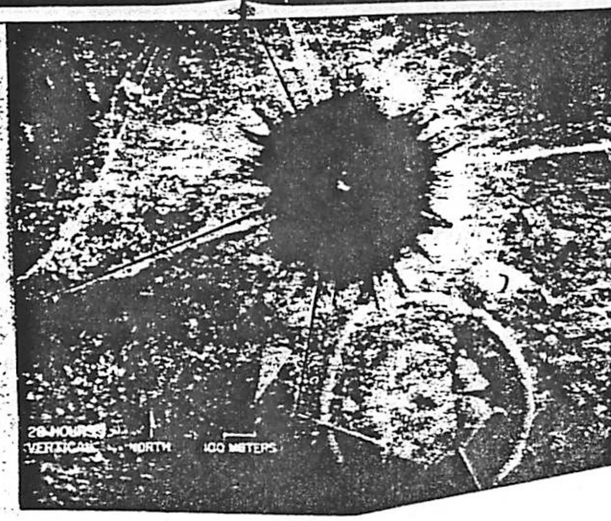

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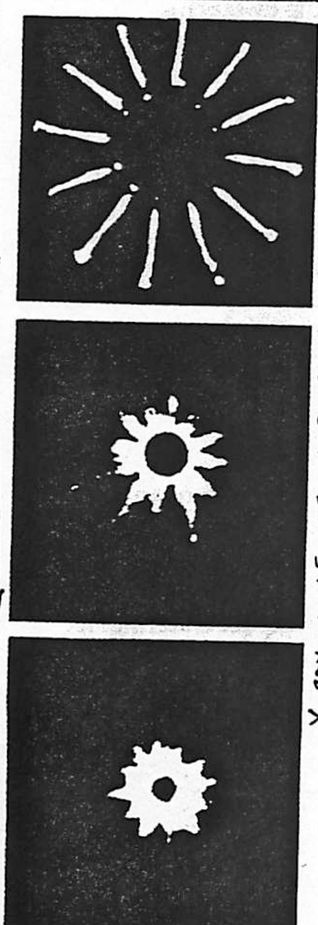
↑

94. Twenty-four hours later Trinity, seen from the air, revealed a radioactive crater of green, glassy, fused desert sand. (Smaller crater to the south marks the 100-ton explosive test.)



X RAY MOVIE OF IMPLOSION : LENSES OF EXPLOSIVE USED TO COMPRESS CORE

95. Los Alamos director Robert Oppenheimer (*left*) subsequently visited the site with Manhattan Project commanding general Leslie R. Groves and found only the reinforcing rods of the tower footings left unvaporized.

↖ X-ray movie of implosion
Note core compression in

Early Rocket Development

Although Russian Pioneer Konstantin Tsiolkovsky had suggested the use of liquid propellants, and Von Braun and the Peenemunders developed the modern rocket, New England scientist Robert H. Goddard was the first to build a working liquid propellant rocket. The first flights were made near Worcester, Massachussets. A subsequent test was thought by locals to be an aeroplane crashing in flames - the local publicity, and the Massachussets weather (these first tests were conducted in snow) prompted a move to sunnier climes.

Money (this was the 1920s) was tight, and Goddard needed funds. He was supported somewhat by the Smithsonian institution, but eventually obtained support (with the help of Col. Charles Lindberg) from the Guggenheim family. He set up his launch tower near Roswell, NM, and developed among other things, gyroscope stabilisation.

Operation Paperclip - White Sands

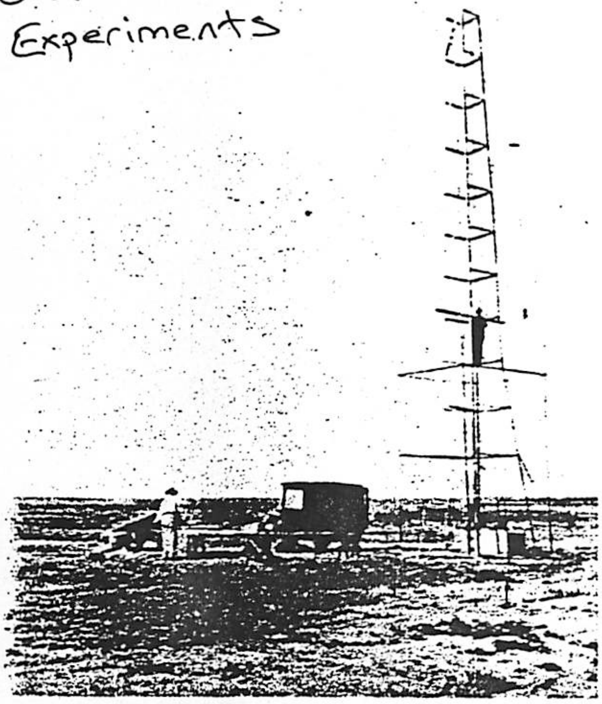
The rocket in its modern form was evolved principally by members of the German VfR (Rocket Society), drafted to work on artillery rockets (see NTS fieldtrip handout). Their experiments (including innovations such as supersonic wind tunnels) were conducted in Peenemunde, on the Baltic coast. The best-known results of their work was the V2 rocket, launched in large numbers at England and Antwerp. Each carried 1 ton of explosive, although a V2 impact, without warhead, causes a crater 120ft in diameter by 45ft deep. Near the end of the war, these scientists (most notably Von Braun) fled southwest (away from the Russians, and to a lesser extent, away from the British sector) and were 'acquired' by the US to work on rockets for them.

The experiments were conducted at the White Sands Proving Ground (an outpost annex of the Ballistic Research Lab of the Aberdeen Proving Ground in MD). The scientists were housed for the most part in Fort Bliss, TX. It became the White Sands Missile Range (by merging with the Navy's range) in 1958. Some 67 V2 rockets were fired, some with upper stages, and these tests (indudign upper atmosphere investigation and space biology) formed the basis for much subsequent development of both space launchers and ballistic missiles

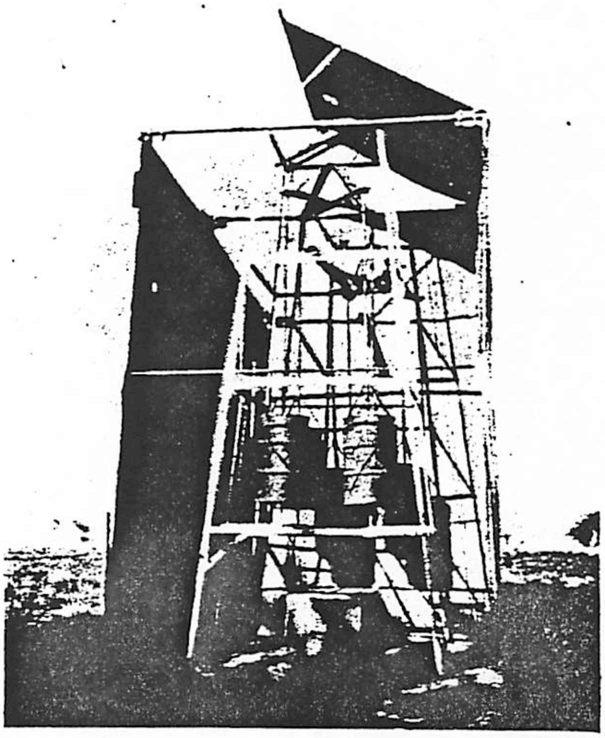
When the US State Department learned of the improper procedures used to import the rocket scientists (and their wives : Paperclip rules did not allow for fiancees, and at least one marriage was hastened as a result) the entire contingent was bussed to Mexico and then immigrated 'properly'. After the V2 experiments ended, most of the Germans were moved to Huntsville. Many subsequently worked for NASA or industry.

The non-obvious Planetary Connection: evaluating the performance of the V2s and their variants required powerful tracking cameras and telescopes. These devices, of long focal length, appealed to an astronomer looking for a change of scene, Clyde Tombaugh. Among Tombaugh's innovations were launching in the evening (11am, with the worst seeing, was until then the preferred launch time), enabling sharp pictures of the rockets at altitudes of 110 miles, and proposing the paint pattern on the rocket (to evaluate attitude dynamics, and determine the resolution achieved by the camera.) One of the cameras, closest to the pad, was used to spectroscopically analyse the engine exhaust. Usually a Na D line was present - prior to one failure, several hydrocarbon lines appeared in the spectrum suggesting incomplete combustion and leading Tombaugh to deduce that the oxidiser pipeline had been blocked.

Goddard's Experiments



1. 60-foot tower, previously used in Auburn and Fort Devens, as erected at Roswell, N. Mex.

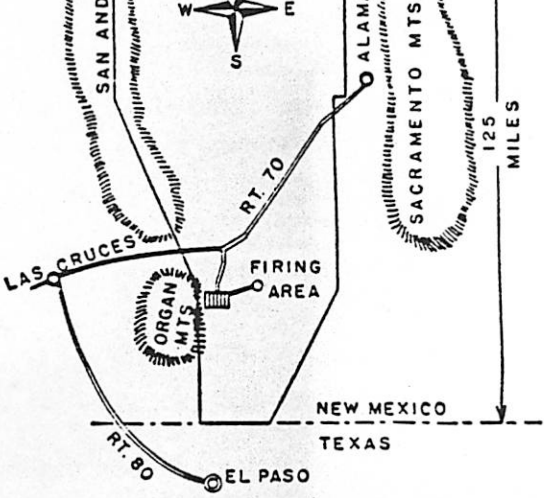


2. 20-foot tower for static tests at Roswell, N. Mex.

FIGURE 7.1

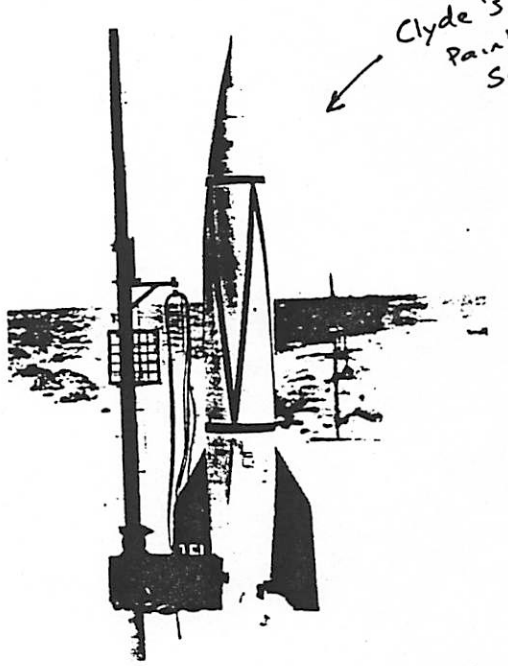
THE WHITE SANDS PROVING GROUND IN NEW MEXICO

Because it is surrounded by mountains and isloated from population centers, the U.S. Army chose this site for the Hermes Project to fire captured V-2 missiles. While some of the team was stationed at White Sands, the bulk of the Germans were at Fort Bliss near El Paso, Texas.



Source: Willy Ley *Rockets, Missiles, and Space Travel* (New York: The Viking Press, 1957).

Clyde's Paint Scheme



NASA, Marshall Space Flight Cent.

Under Project Hermes, 67 V-2s were launched and the technology transferred to the American team learning about rockets. Pictured here is a launch at White Sands on August 22, 1951. This rocket attained a 132 mile altitude, the highest ever reached by a V-2.

Radar

Radar saw its development principally in Europe in the 20s and 30s. After some enquiries into whether new-fangled short-wavelength wireless transmissions could be used as a 'death ray', it was decided in Britain (by Scottish scientist Robert Watson-Watt) that radio echoes might give warning of bomber attack. Inspired long-range planning prompted the construction of a girdle of radar stations ('Chain Home') around Britain's south coast in the '30s. When war and the Luftwaffe came, the radar allowed British fighters to be vectored onto the squadrons of incoming bombers : without it, the fighters would have been spread too thin (prompting Churchill's famous 'Never, in the field of Human Conflict, has so much been owed, by so many, to so few'). One propaganda ruse was that British pilots were fed a carrot-rich diet, the extra vitamin A supposedly aiding their night vision, when in fact radar was guiding them to their targets.

New Mexico's role in radar, ironically, is in defeating it. It hosts a radar range, on which the radar cross section ('RCS" - in simple terms, the size of the 'blip' ; astronomers may think of it as albedo*area) of aerospace vehicles (and nuclear-tipped re-entry vehicles in particular) could be measured.

In 1976, two contractors Northrop, and Lockheed fielded their models for a low-observable (='Stealth') fighter. The models are mounted on poles and the echo strength measured. But, as nothing with so small an RCS had been measured, and the poles dominated the echo. Northrop and Lockheed then had to provide (at their own expense - some $500k - a set of 'stealth' poles. Lockheed's aircraft won the competition, with an RCS of about a square inch.

The internal Lockheed code name for the project was 'Hopeless Diamond' ; the Air Force program was 'Have Blue'. The F-117A stealth fighter (actually a 'strike plane' or light bomber) first flew in anger in the US attack on Panama, and with more fanfare, in the Gulf. It has the official name 'Nighthawk', but because of its flat underside has also gone by the informal name 'frisbee', and the more picturesque 'Wobbly Goblin' (referring to its unconventional appearance, and the fact that the stealth shape makes the aircraft unflyable without 'fly-by-wire' stability augmentation. Most of the F-117As are based at Holloman AFB in New Mexico, not far from Roswell.

Planetary Connection : The stealth planes (and indeed the Stealth Ship Lockheed also developed) have low RCS not by absorbing the radar radiation, but rather by reflecting it away (in a direction away from the observer. Most radars are monostatic (i.e. the transmitter and receiver are co-located) so radar observations are made 'at opposition'. A radar receiver some distance from the transmitter ('bistatic') might do rather better at spotting a stealth plane.

The Galilean satellites have an 'inverse' stealth behaviour. Coherent backscatter leads to a strong backscatter gain (i.e. the radiation is reflected back towards the observer, like on reflective road signs) such that the radar reflectivity is >1. Conservation of energy dictates that the reflectivity cannot be >1 in all directions.

Bibliography

Richard Rhodes, The Making of the Atomic Bomb, Simon and Schuster NY 1986
Robert H Goddard 'Rockets' American Rocket Society, NY 1946
Deiter Huzel 'Peenemunde to Canaveral' Prentice-Hall 1962
Marsha Freeman 'How We Got to The Moon : The Story of the German Space Pioneers' 1993
David Levy 'Clyde Tombaugh : Discoverer of Planet Pluto' UA Press 1991
Ben R. Rich 'Skunk Works' Brown Little, Boston 1994
Alfred Prince 'Instruments of Darkness : The History of Electronic Warfare' Scribner NY 1977

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Speleology of the Carlsbad Region

plus a short course on cave formation and cave formations

with your guide to the narrow, winding passages of knowledge

Barbara Cohen

Caves can form in two different ways:

- **erosion** of a massive formation (limestone caves, sandstone caves, sea caves, gypsum caves, and ice caves)
- **enclosing** a space (boulder caves and lava tubes)

It turns out, though, that nearly 95% of the world's caves are in limestone. What makes limestone such a great cave-host?

Limestone

- sedimentary rock made up almost entirely of ***calcite*** $CaCO_3$
- formed on ocean bottoms out of shells, coral, and chemical precipitate
- soluble in dilute acids

Usually weak carbonic acid carves out caves when water comes into contact with air or decaying organic matter:

$H_2O + CO_2 \rightarrow H_2CO_3$ (carbonic acid)

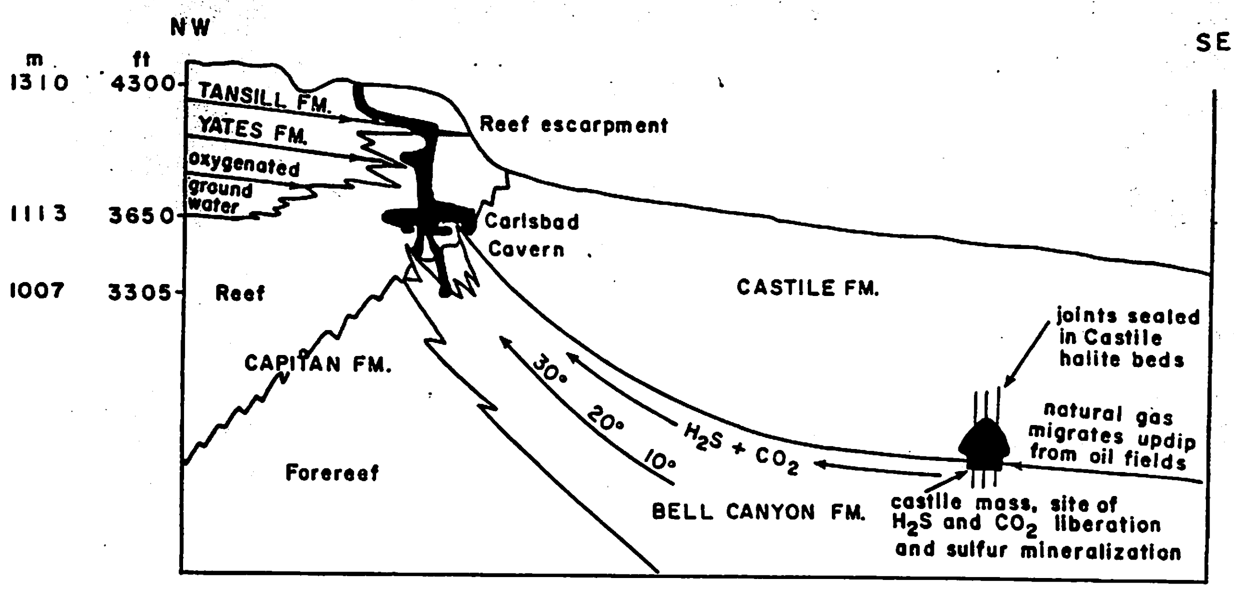
$H_2CO_3 + CaCO_3 \rightarrow Ca^{++} + 2HCO_3^-$ (calcium bicarbonate solution)

Carving Carlsbad Cavern

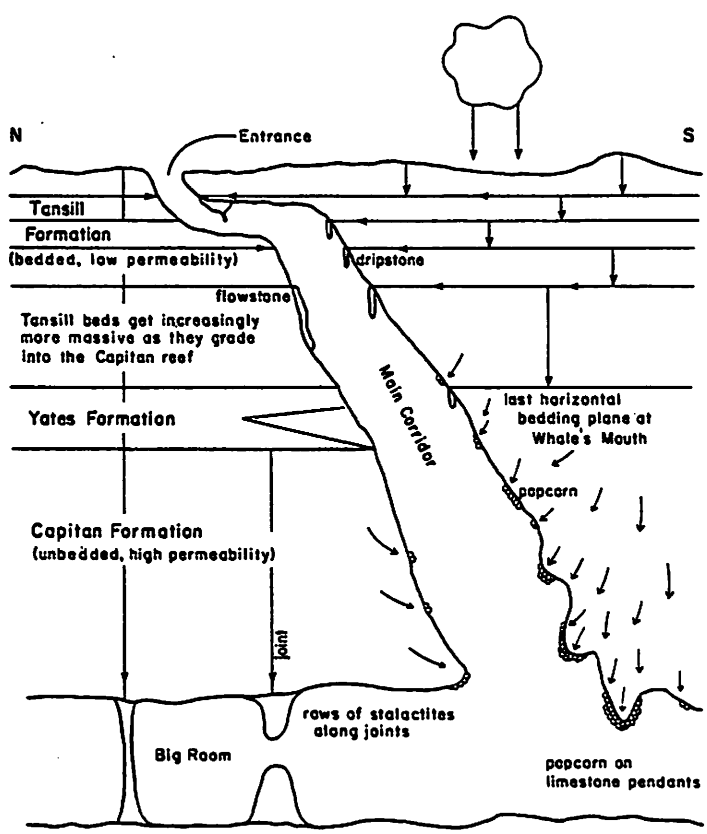
The Carlsbad cave system is formed primarily in a massive member of the Capitan Limestone of the Permian Reef. The caverns are developed along a series of joints that are parallel and perpendicular to the reef front. Passages are confined to the limestone reef, sandwiched between the dolomitic (Mg-calcite) forereef and backreef areas. These caverns were formed primarily by a sulfuric acid reaction:

$H_2S + 2O_2 \rightarrow H_2SO_4$ (sulfuric acid)

$H_2SO_4 + CaCO_3 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O$ (gypsum) $+ H_2O + CO_2$



The H_2S came from the natural gas deposits of the Castille formation. As the H_2S moved upwards, it mixed with O_2-rich groundwater and made sulfuric acid. The dissolution mechanism forms gypsum, but most of the gypsum in the beginning was redissolved and carried out.



THE BIG ROOM IN CARLSBAD CAVERNS IS THE 9TH LARGEST

SINGLE CHAMBER IN THE WORLD (BY SURFACE AREA) !

Carlsbad Cavern History

>112,000 yrs ago entrance opens (ground sloth remains)
Pictographs in entrance show Native American interest
1800's ranchers knew about cave
1903 guano mining begins
1923 National Monument
1930 National Park

The life cycle of a cave

Limestone caves are always relatively young, because the same forces that create them go on to destroy them (causing sinkholes, or karst topography).

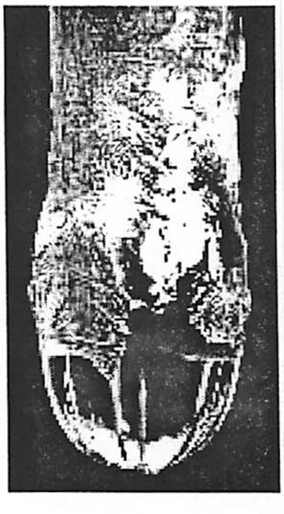
❶ massive limestone bed created
❷ stresses cause joints and fractures in the rock
❸ rock in *zone of saturation*--under the water table
❹ water moves through cracks and dissolves rock
❺ rock moves up or water table moves down--*zone of aeration*
❻ caves exposed, cave formations begin
❼ caves dry up, formations crumble
❽ cave collapses

SPELEOTHEMS

As water flows through the limestone layer surrounding the cave, it becomes super-saturated with calcium carbonate. When the water finds its way into the cave, the calcite precipitates out into structures based on the mode of deposition. Such structures are called **speleothems** (Gr: *spelaion* "cave" and *thema* "deposit"). Very often, precipitation occurs along crystal orientations, such that a speleothem can appear to be one large crystal. Speleothemic calcite is also known as ***travertine***.

Dripping Water:

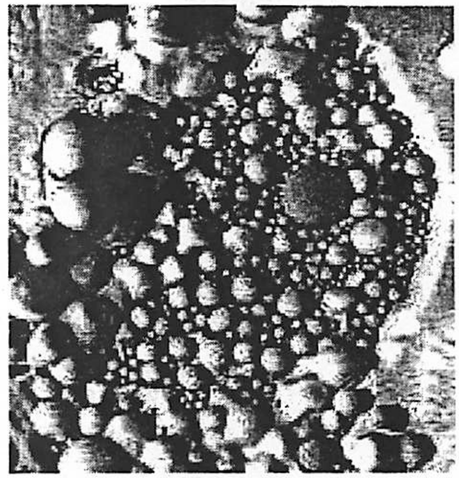
Stalactites are icicle-like calcite structures that hang down. Drops of water form on the ceiling, deposit calcite, and drip down. Successive drops follow the inside of the deposit, leaving rings that form ***soda straws***. The familiar carrot shape forms as water flows along the outside, adding to the outside as well as the bottom. ***Stalagmites*** rise from cave floors. As drops of water fall to the floor of a cave, they deposit calcite in a concentrated mound. Stalagmites may look like inverted stalactites, but are morphologically different. They have no central tube and are generally rounder, thicker, and smoother than stalactites. ***Columns*** form when a stalagmite and a stalagmite meet.



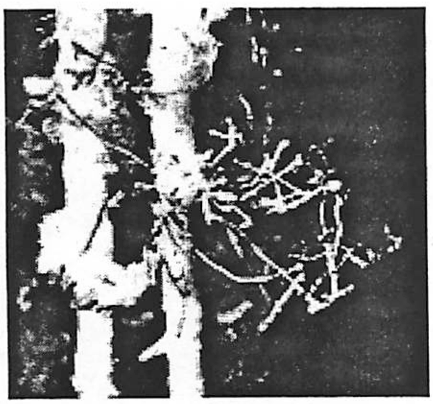
ITS AREA IS 38,000 SQUARE METERS (ABOUT 14 FOOTBALL FIELDS)

Flowing Water:

As water flows into a cave, it often follows the existing cave walls and contours. The precipitated calcite then coats the walls and floors with solid ***flowstone***. If flowstone coats something that is later eroded, like a pile of sand, the unsupported flowstone is called a ***canopy***. ***Draperies*** begin when water flows along an inclined ceiling and leaves a tiny ridge. As more water follows the trail, calcite builds downwards in a thin sheet. Discolored water can give draperies a banded appearance, and they are sometimes called ***bacon***. ***Rimstone dams*** are small, curved walls of calcite that hold back crescent-shaped pools of water. As a stream flows over a rough spot in the cave, the water is agitated, loses CO_2, and deposits calcite, beginning the lip of a dam. ***Cave pearls*** form in shallow pools beneath a steady flow of water. Calcite precipitates around grains of sand, much in the same manner as real pearls in oysters. After much growth, the pearls sink to the bottom and become cemented to the pool floor.



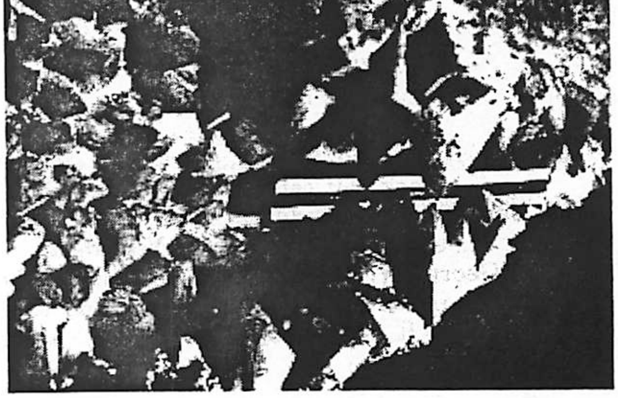
Seeping water:



Helictites start as tiny stalactites, leaving rings of calcite. Water then travels to the tip by capillary action, and so the resultant formation is not controlled by gravity. Helictites are sometimes horizontal and can be quite twisted. ***Shields*** begin like two draperies, where two lines of calcite are deposited and begin to form plates. Then, water seeps between the plates and the shield grows outward. Because they form by something akin to capillary action, shields can project from walls and floors as well as ceilings. ***Cave coral*** are small, knobby clusters of calcite that stem out away from walls and ceilings. They are common along cracks in walls or on porous deposits of silt.

Still Water:

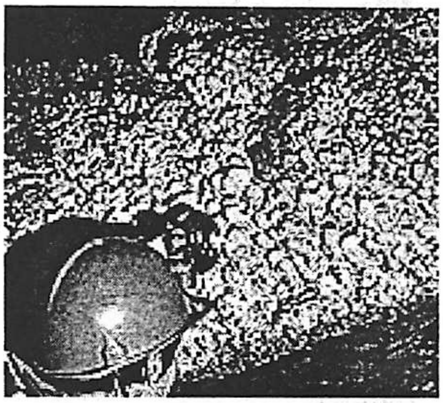
Lily pads and ***cave rafts*** form when a thin layer of calcite forms over a pool of water. Lily pads are often connected to other speleothems like stalagmites. ***Dogtooth spar*** are calcite crystals that grew slowly and euhedrally in submerged rooms. The long, pointed crystals look like rows of teeth.



AND ITS CEILING RISES 75 METERS ABOVE THE FLOOR (1.5 TIMES THE HEIGHT OF NIAGARA FALLS)!

Water Vapor:

The air in a cave room can become moist with water vapor, and the vapor is often supersaturated with calcite. This calcite precipitates from the atmospheric vapor onto the cave wall, forming ***popcorn***.



Not strictly speleothems:

Behind the walls of the cave, there is still fractured limestone. Sometimes the cracks are filled with secondary calcite. When the cave walls erode back to expose the calcite veins in relief, they are called ***boxwork*** (because the joints are often perpendicular to each other). When the original limestone formed, there were probably impurities incorporated into the rock, like sand, clay, and chert. As the cave weathers out, these impurities fall from their positions in the rock to piles on the floor and are termed ***cave fill***. ***Fossils*** form when the shells and skeletons of sea creatures get incorporated into an undersea limestone bed. ***Breakdown blocks*** are fallen pieces of cave walls and floors. They can range in size from pebbles to house-sized rocks. Breakdown processes usually occur either very early or very late in the cave's lifetime; mature rooms with arched ceilings are remarkable stable structures. ***Moon milk*** is a soft, white material found on the floors and walls of some caves. It is a mixture of minerals formed by bacterial action.

Gypsum ($CaSO_4 \cdot 2H_2O$) is a common byproduct of cave formation in sulfide-containing limestone. When deposited as speleothems, gypsum is often in fibrous or silky forms like ***selenite needles*** or ***cave ropes***. In the Carlsbad region, though, massive (nonspeleothemic) gypsum occurs as well.

Elemental sulfur in the Carlsbad region occurs as sprays, rosettes, or crusts that overlie late-stage speleothems or bedrock. The sulfur formed subaerially from the oxidation of hydrogen sulfide rather than the reduction of gypsum:

$$2H_2S + O_2 \rightarrow 2S + 2H_2O$$

Courbon et al. *Atlas of the Great Caves of the World*. (St. Louis: Cave Books) 1989
Gurnee, Russell and Jeanne, *Gurnee Guide to American Caves*. (Teaneck NJ: Zephyrus Press Inc.) 1980.
Hill, Carol A., *Cave Minerals*. (Austin TX: The Speleo Press) 1976
Love et al., ed. *Carlsbad Region, New Mexico and West Texas*. (New Mexico Geological Society) 1993
Moore, George W. and G. Nicholas Sullivan, *Speleology: The Study of Caves*. (Teaneck NJ: Zephyrus Press Inc.) 1978
Shaw, Trevor R. *History of Cave Science*. (Australia: Sydney Speleological Society) 1992.

Journal of Volcanology and Geothermal Research, 59 (1993) 59–75
Elsevier Science Publishers B.V., Amsterdam

Emplacement of the 75-km-long Carrizozo lava flow field, south-central New Mexico

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ABSTRACT

The Carrizozo Lava flow field is a young, 75-km-long, compound tube-fed pahoehoe flow field located in south-central New Mexico. Topographic channeling, unusually low viscosity, and fissure vents are ruled out as possible explanations for the length of the flow field. Effusion rates are estimated using: (1) a Bingham plastic model; (2) correlations between flow morphology and effusion rate; and (3) comparison with Hawaiian pahoehoe flows. The Bingham plastic model placed no useful restrictions on the effusion rate, while empirical and theoretical correlations gave estimates between 300 and 3×10^5 m^3 s^{-1} for the effusion rate. The striking morphological similarity of the Carrizozo flow field to the compound tube-fed pahoehoe Kupaianaha flow field on Kilauea Volcano suggests an effusion rate of about 5 m^3 s^{-1} and an eruption duration of nearly 3 decades. This long eruption duration and a long-lived lava tube system are interpreted to be the most important factors responsible for the length of the Carrizozo flow field. Furthermore, we conclude that the Bingham plastic model does not apply to tube-fed pahoehoe flow fields and that the correlation techniques grossly overestimate their effusion rates. This indicates that effusion rates may also have been overestimated for extra-terrestrial lava flows where it is has not been possible to distinguish between pahoehoe and 'a'a.

Introduction

The 75-km-long Carrizozo Lava flow field provides a valuable opportunity to examine the factors that produce long basaltic lava flows on the Earth and elsewhere. While investigating the factors responsible for the great length of the Carrizozo flow field, this paper also examines a variety of techniques used to determine effusion rate, eruption duration and lava rheology from remote sensing data from inactive lava flows. Thus, in addition to understanding the emplacement of the Carrizozo flow field itself, we also wish to test the usefulness of these techniques in studying the emplacement of the several hundred kilometers long lava flows that are seen on Venus, the Moon, and Mars.

The Carrizozo flow field is particularly well suited for this study because of its great length, simple planimetric form, and well preserved primary morphology. Many lava flows of comparable length are less well suited. For example, the 160-km-long Undara flow in Queensland, Australia (Stephenson and Griffin, 1967) and the 103-km-long Tappen Wash flow in Arizona (M. Malin, pers. commun., 1989) are extensively weathered and are confined by narrow river channels. In other cases, such as the 52-km-long 1859 Mauna Loa flow, the lava flows have ended in the sea and their total length is indeterminate.

The Quaternary Carrizozo flow field is located in the Tularosa Basin in south-central New Mexico (Fig. 1). Previous work on the flow field includes general description during geologic mapping (Allen, 1952; Weber, 1964; Smith, 1964), major- and trace-element anal-

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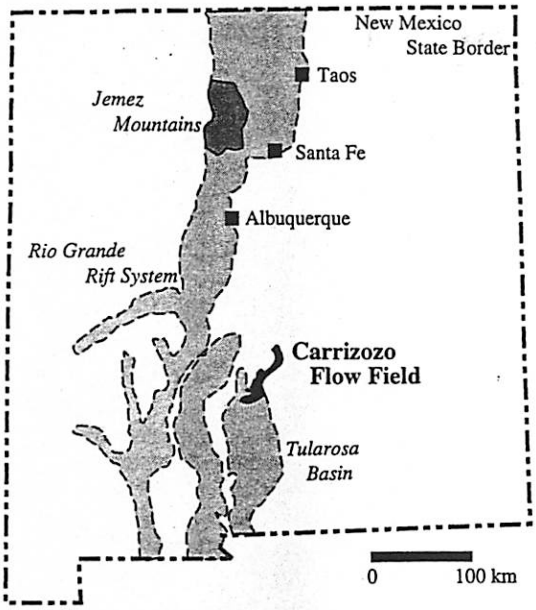


Fig. 1. Location of the Carrizozo flow field and the Tularosa Basin with respect to the Rio Grande Rift (after Clemons et al., 1982).

yses (Renault, 1970; Farris, 1980) and morphological description (Theilig, 1986). The lavas are intermediate in composition between alkalic and tholeiitic basalts and are part of the volcanism associated with the Rio Grande rift (Renault, 1970). The flow field has a maximum length of 75 km and a surface area of 330 km^2 (Allen, 1952).

Both airborne remote sensing and ground truth data were collected for this study. The Carrizozo flow field was overflown by NASA aircraft in May 1988 and September 1989 with the Thermal Infrared Multispectral Scanner (TIMS), NS-001 Landsat Thematic Mapper Simulator, and a Zeiss color photometric camera. The TIMS instrument has 6 channels covering the 8–13 micron wavelength region and a spatial resolution of 11–19 m/pixel (NASA-Ames Research Center, 1989). The NS-001 instrument has 7 channels similar to the Landsat Thematic Mapper in the 0.45–2.3 micron region and an additional thermal infrared channel at 10.4–12.5 microns and a spatial resolution the same as that of TIMS (NASA-Ames Research Center, 1989). The air photos provide stereoscopic coverage over the entire flow with sub-meter spatial resolution. Ground truth data consist of four days of field work involving still photography, magnetometer surveys and rock sample collection.

Morphology of the Carrizozo flow field

The single most striking feature about the Carrizozo flow field is its 75 km length. It covers 330 km^2 to an estimated depth of 10–15 m, for a total erupted volume of about 4.3 km^3 (Allen, 1952). The flow field is 1–5 km wide and runs down the center of the Tularosa Basin (Fig. 2). USGS 7.5′ quadrangle topographic maps show that the nearly planar basin floor dips at an angle of 0.2–0.4° toward the south. For a fraction of its length, the Carrizozo flow field abuts the mountains at the edge of the basin. The flow field is also diverted around some local topographic highs, but has surrounded others, forming kipukas (islands) of the underlying sedimentary rocks. Overall, to-

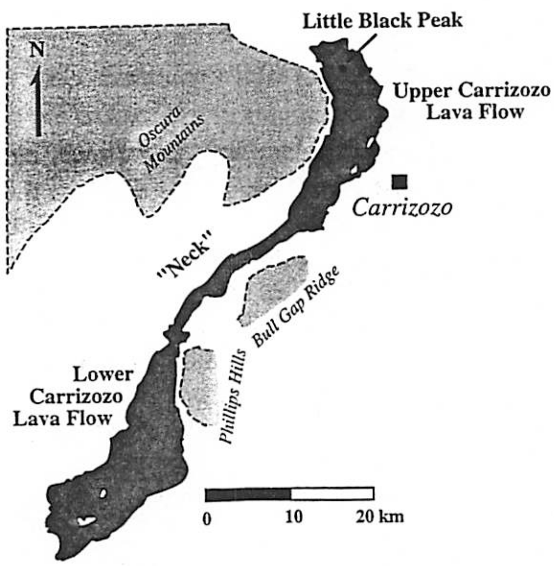


Fig. 2. Main physiographic sections of the Carrizozo flow field. The flow field is topographically constrained only along the northern half of the western side of the Upper Carrizozo Lava Flow and the southeastern side of the "neck" region.

Laccolith Mountains Near the Carrizozo Lava Field

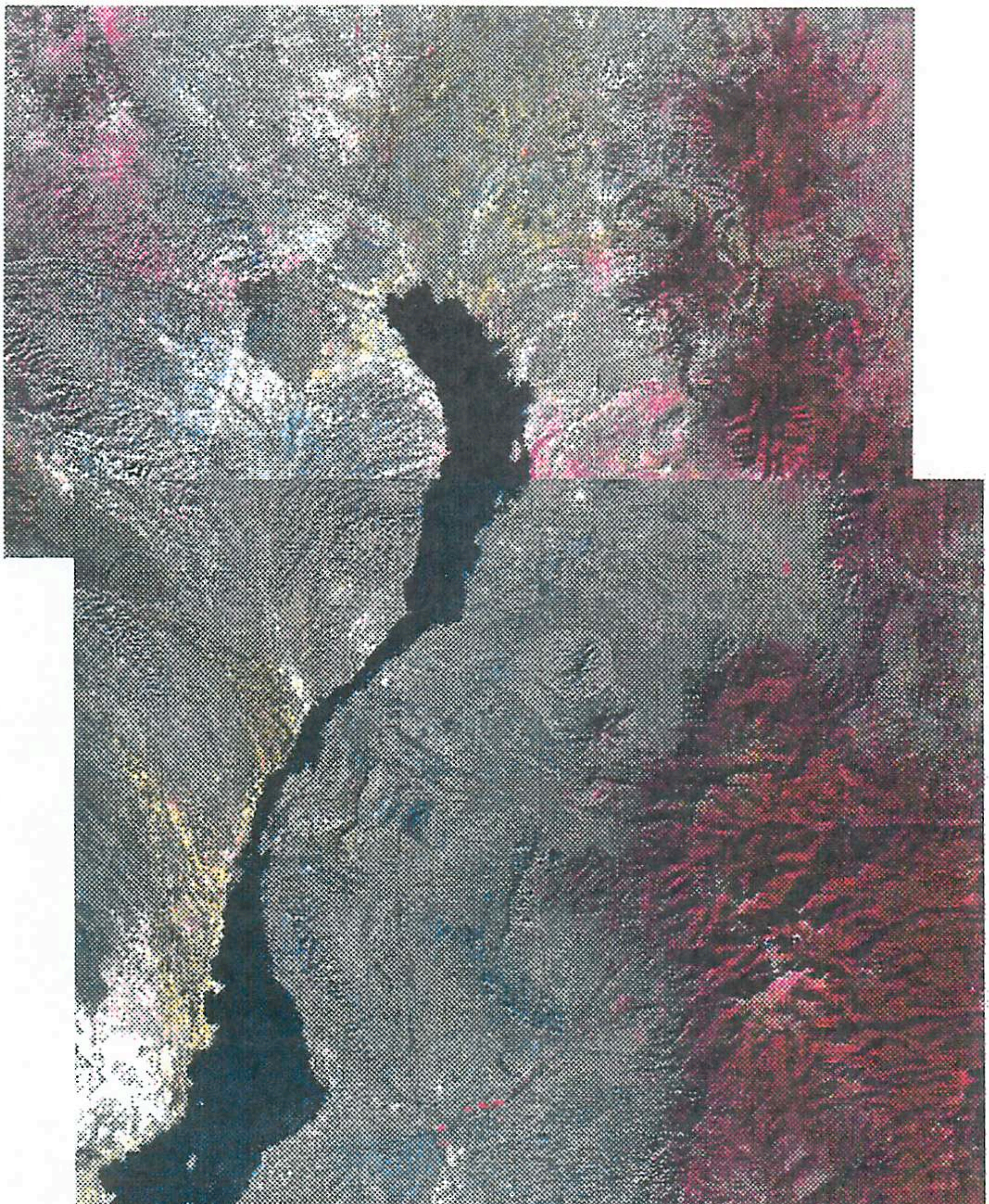
Joe Spitale

A laccolith can form when a pocket of magma becomes trapped in the rock layers before reaching the surface. It is a type of sill with a flat bottom and a domed top. Several such structures lie near the Carrizozo lava fields and should be visible to the north of highway 380.

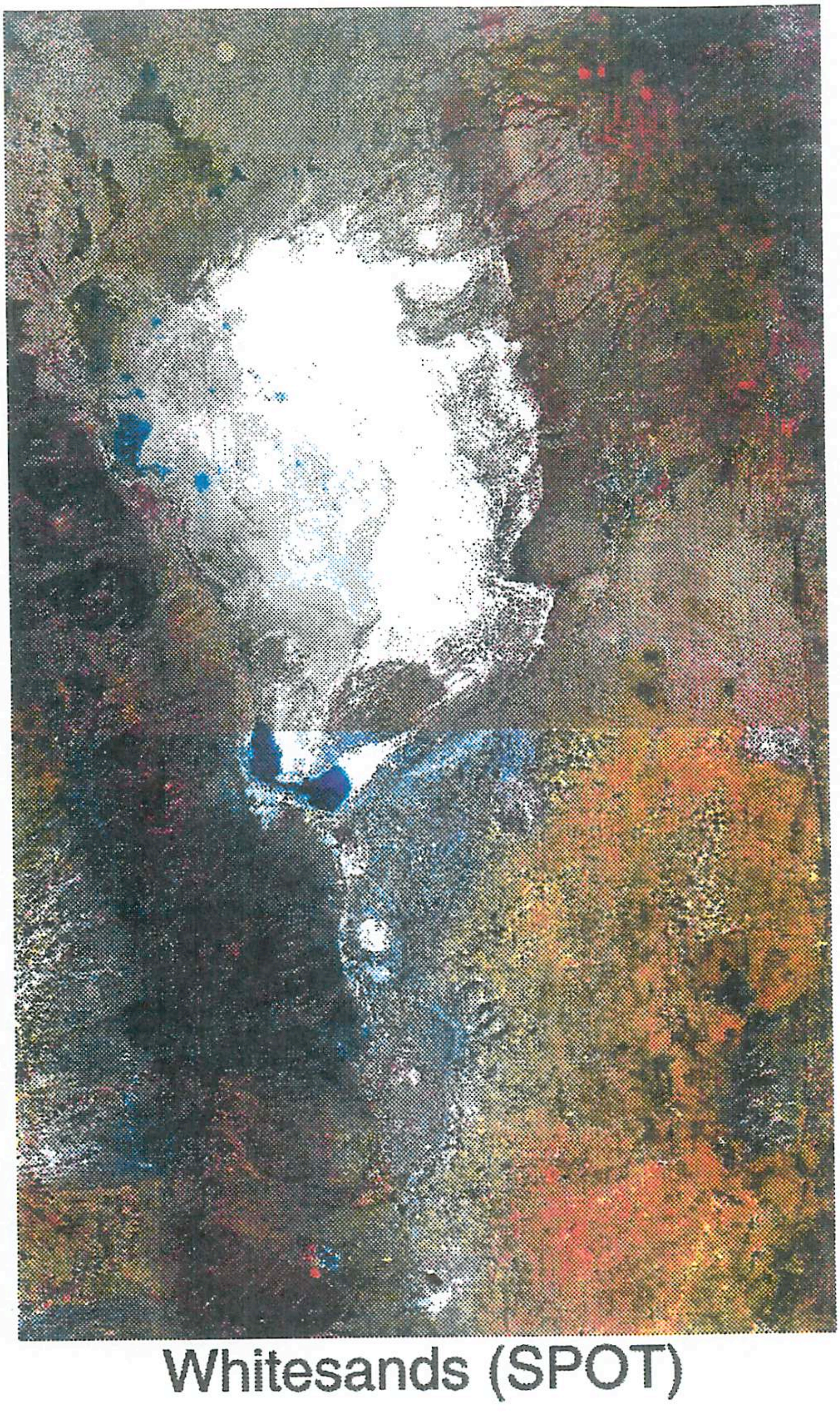
Capitan mountain lies north of milepost 315. Its elongated shape suggests intrusion through an east-west fissure [1]. Carrizo mountain is located several miles to the west of that, just east of the northern head of the lava fields and is visible as a ringed structure near the top-right in the adjoining satellite image of the lava fields[2]. Its ringed appearance is caused by the erosion of overlying sedimentary layers which were originally pushed upward into a dome over the intrusion.

References:

1. Halka Chronic; *Roadside Geology of New Mexico* Mountain Press, 1987
2. http://www.spot.com; Catalogue of images from the French SPOT satellites



Carrizozo Volcanic Field (SPOT)



Whitesands (SPOT)

Model of An ERapting Volcano

Usings simple kitchin Materials Students can Model lava flowing from a Volcano.

yoall need: 1/2C vinegar 1/2C Liquid Dish soaP, Red food colouring Empty frosen Juice container baking soda, jar

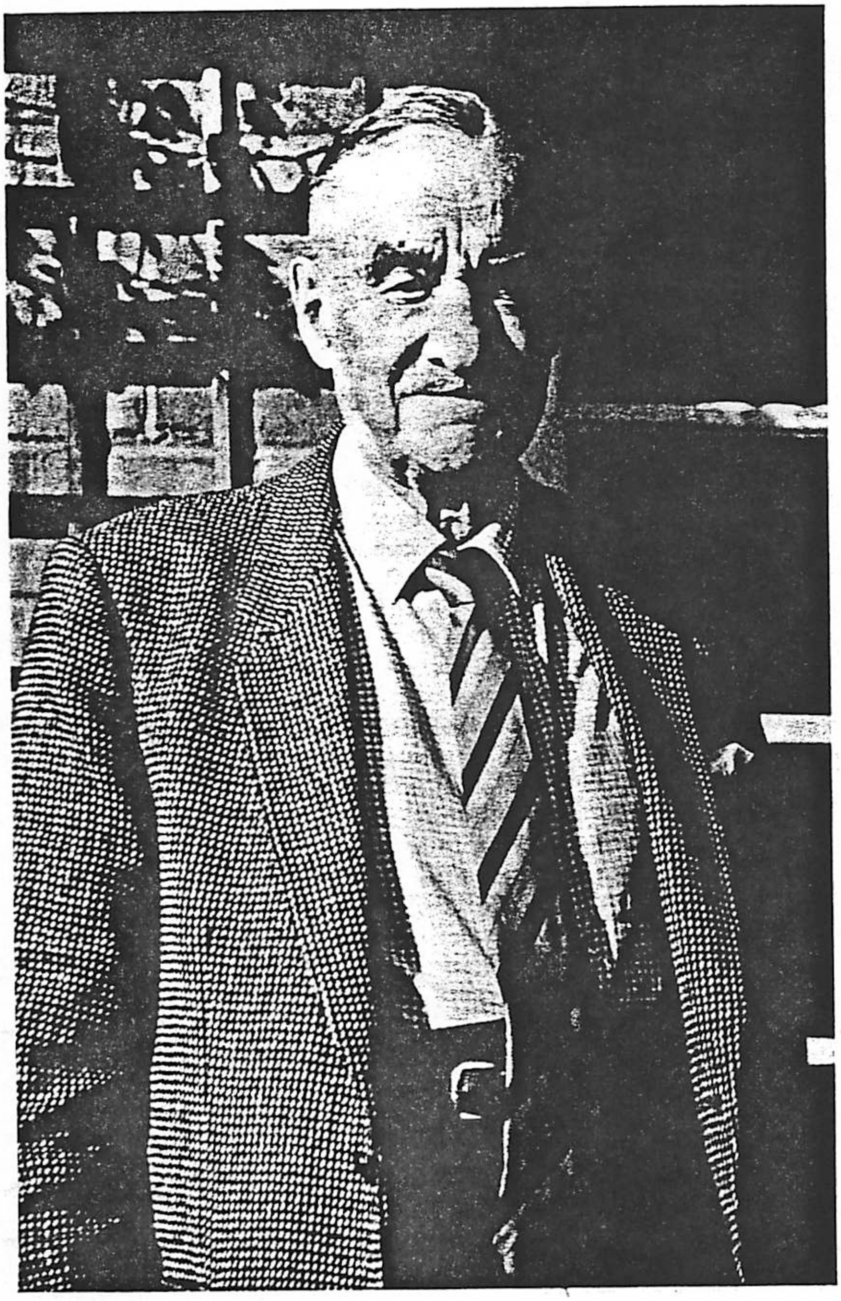
Directions: Mix first 4 Ingridiants In Jar. Make a Hill with Juice container In Middle OF Hill. put Baking Soda In Juice container then pour Mixture In Tradaaaa!!!!

Ian McEwen

DUNE

(soundtrack by Toto)

as told by David Muad'dib



Ralph Bagnold, THE MAN for the physics of dunes. His book, The physics of blown sand, is the bible for dune studies. Written in 1941, based on research done in the Libyan desert (see The English Patient).

Brigadier Ralph Alger Bagnold F.R.S.

How do sand particles move? Saltation, suspension, and creep (roll). Like stop, drop, and roll, only better.

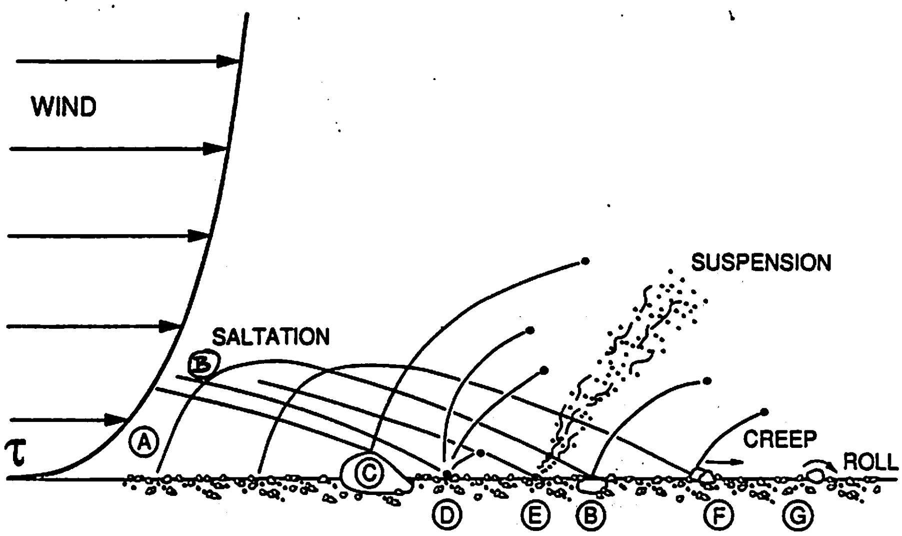


Fig. 5. Diagram showing the four principal modes of aeolian transport of grains on Venus: surface shear stress (τ) exerted by the wind causes grain (A) to lift off the surface, carries it downwind back to the surface where it bounces (B) back into flight; this motion is termed *saltation*; grain at (C) hits a large rock – possibly causes some erosion – and elastically rebounds to a relatively high saltation trajectory; grain at (D) strikes the surface and 'triggers' other grains into saltation; grain at (E) strikes the surface containing very fine particles (too fine to be moved by the wind alone in this case; see threshold curve Figure 6) and sprays them into the wind where they are carried by turbulence in *suspension*; grain at (F) strikes larger grain and pushes it downwind a short distance in a mode of transport termed *impact creep*, or *traction*; wind alone may also *roll* (G) some grains across the surface.

Formation of the slip-face of a dune. As the wind passes over the top of the dune, the flow becomes turbulent and drops the load on the back side of the dune.

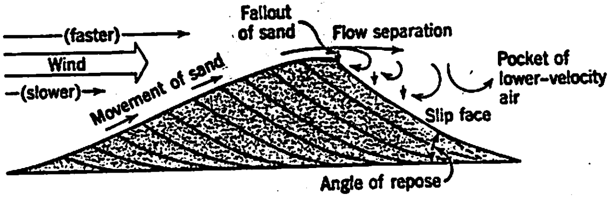
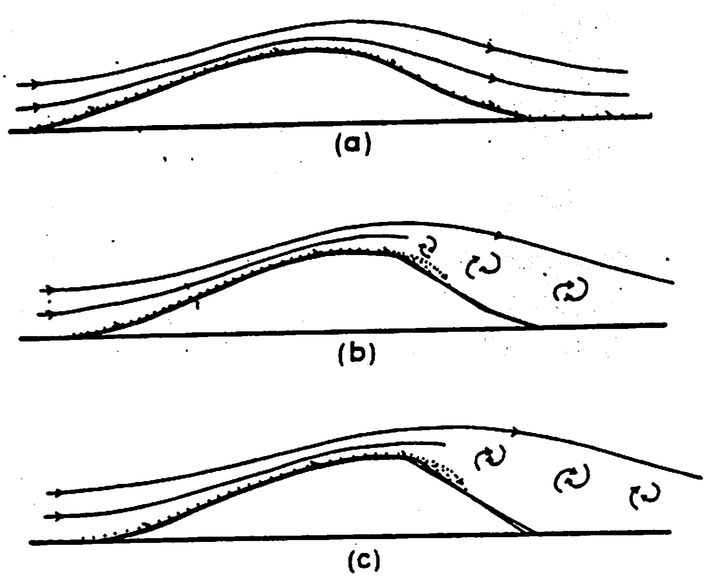
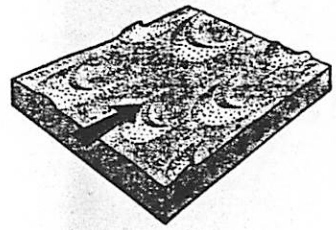
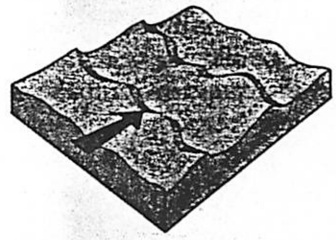
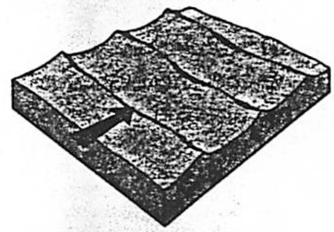
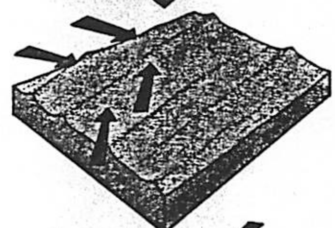
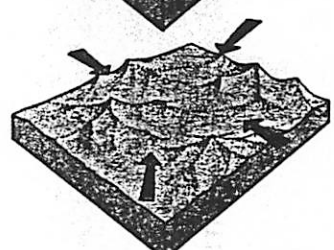
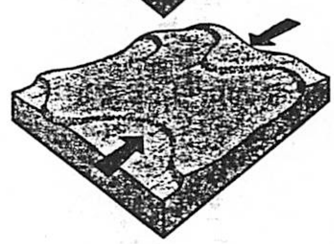


FIGURE 12.25 Cross section through a dune showing development of windward and leeward slopes, and internal stratification.



Principle types of dunes based on forms. These things are cool. In White Sands, there are dome dunes, parabolic dunes, and transverse-barchan dunes.

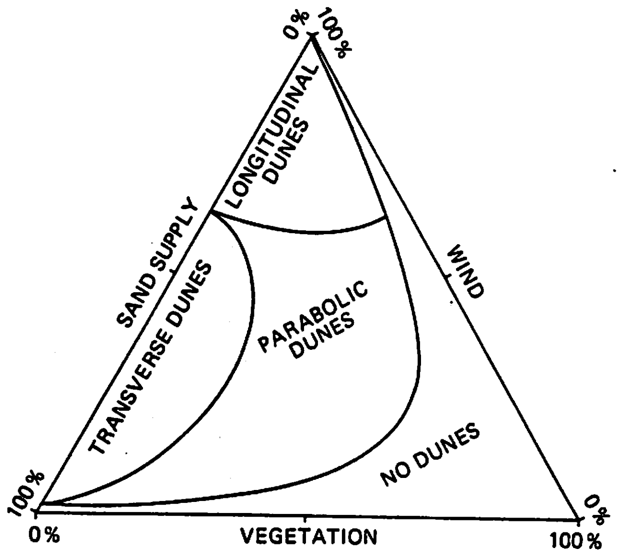
TABLE 12.1 *Principal Types of Dunes Based on Form*

Dune Type	Definition and Occurrence	
Barchan dune	*A crescent-shaped dune with horns pointing downwind.* Occurs on hard, flat floors of deserts. Constant wind and limited sand supply. Height 1 m to more than 30 m	
Barchanoid ridge	*A row of connected crescent-shaped dunes* oriented transverse to wind direction.	
Transverse dune	*A dune forming an asymmetrical ridge transverse to wind direction.* Occurs in areas with abundant sand and little vegetation. In places grades into barchans	
Parabolic dune	*A dune of U-shape with the open end of the U facing upwind.* Some form by piling of sand along leeward and lateral margins of a growing blowout in older dunes	
Linear dune	*A long, straight, ridge-shaped dune parallel with wind direction.* As much as 100 m high and 100 km long. Occurs in deserts with scanty sand supply and strong winds varying within one general direction. Slip faces vary as wind shifts direction	
Star dune	*An isolated hill of sand having a base that resembles a star in plan.* Ridges converge from basal points to central peak as high as 100 m. Tends to remain fixed in place in area where wind blows from all directions	
Reversing dune	*An asymmetrical ridge intermediate in character between a transverse dune and a star dune.* Forms where strength and duration of winds from nearly opposite directions are balanced.	

(*Source:* After McKee, 1979)

What kind of dunes are likely to form in what regimes? Check out the triangle below.

Fig. 5.8. Diagram showing the relationship of the three main dune forms to vegetation, sand supply, and wind. (From Hack, 1941.)



Threshold friction speed (picks up particles, basically) versus particle diameter, for different planets.

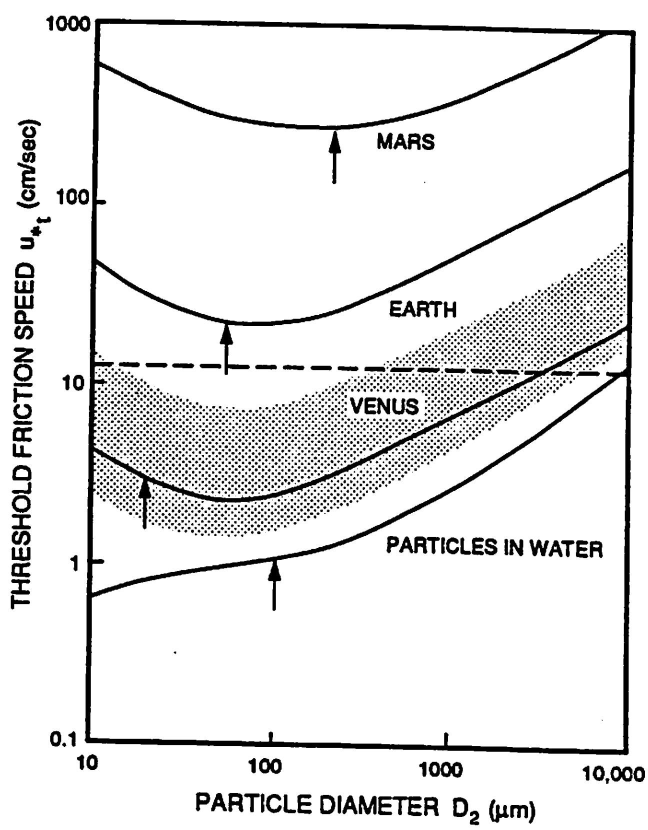
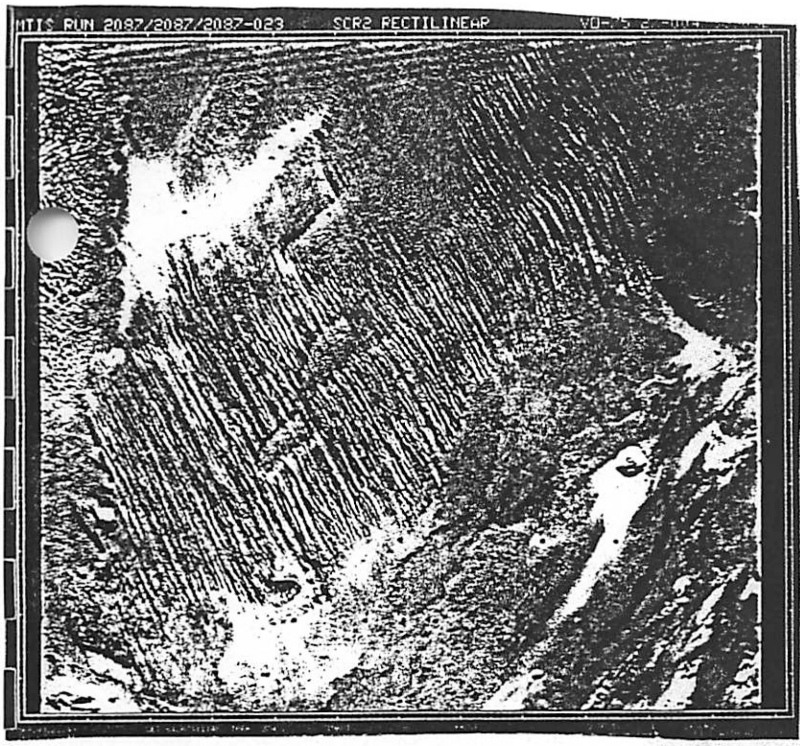


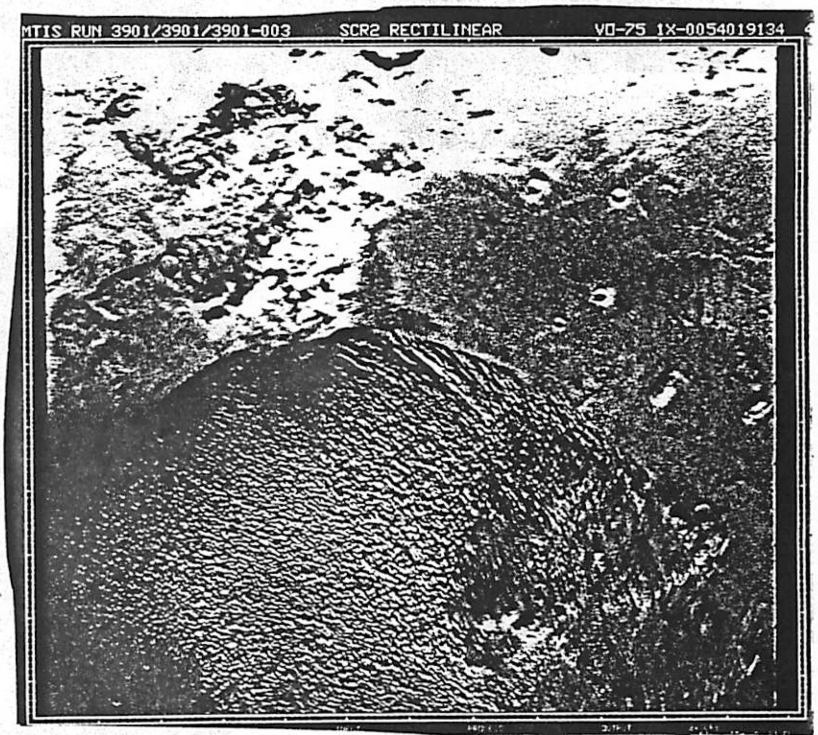
Fig. 6. Threshold friction velocity as function of particle size for Earth, Mars, and Venus in air, compared with threshold in water on Earth: arrow indicates the transition between suspension threshold for small grains to saltation threshold for larger grains. Shaded zone gives range for Venus from the lowest elevations (lowest threshold) to the highest elevations: dashed line corresponds to highest wind velocity measured at the Venera landing sites (from Iversen *et al.*, 1976 and Greeley *et al.*, 1984a).



Yardangs on Mars.

...To begin your study of the life of Muad'dib, then, take care that you first place him in his time: born in the 57th year of the Padishah Emperor, Shaddam IV. And take the most special care that you locate Muad'dib in his place: Arrakis. Do not be deceived by the fact that he was born on Caladan and lived his first fifteen years there. Arrakis, the planet known as Dune, is forever his place.

--from the "Manual of Muad'dib and Geological Field Trips," by the Princess Irulan



More dunes on Mars.

Fig. 14b. Enlargement of area indicated in Figure 14a, showing dunes and radar-bright streaks.

More dunes on Venus.

Yardangs on Venus. Neat!

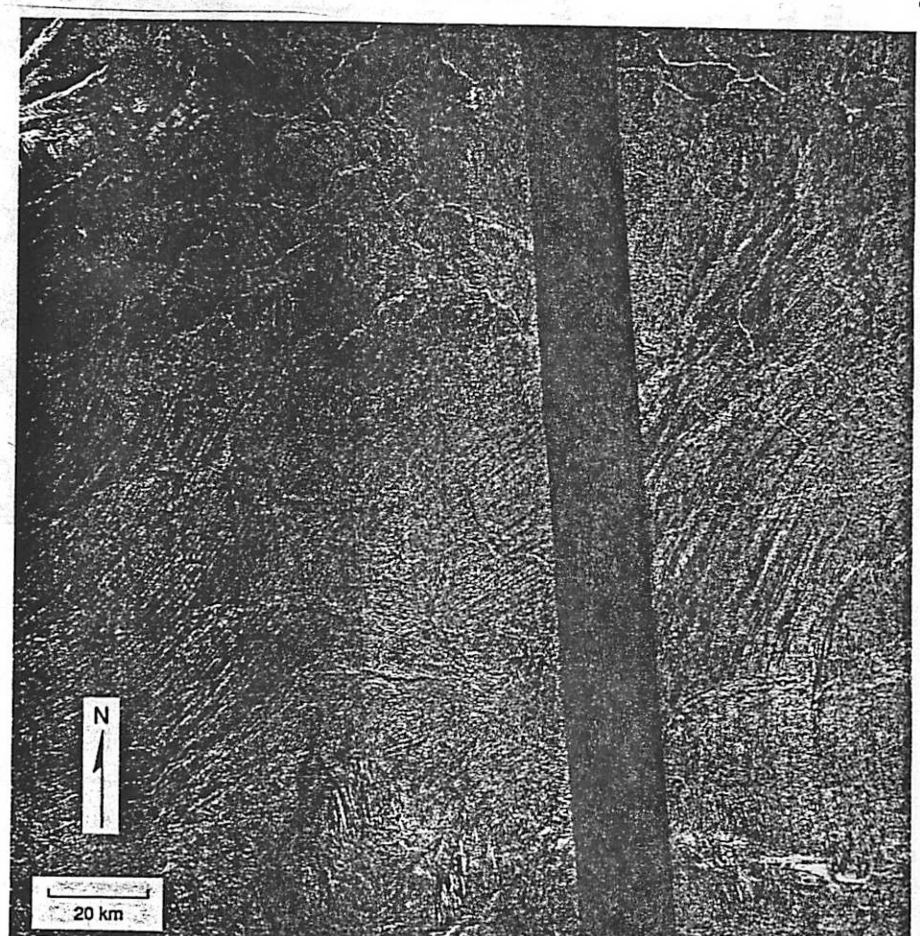


Fig. 17a. Venus yardangs, centered at 9°N, 60.7°E; area shown is ~200 km by 200 km (Magellan MRPS 37879)

References: Skinner and Porter, 1987. Bagnold, 1941. Bagnold, 1988. Greeley et al., JGR, 1992. Greeley and Arvidson, EM&P, 1990. Greeley and Iverson, 1985.

Where oh where are the dunes on Titan?

(The Morphology of Dunes--White Sands Nat'l Mon.)

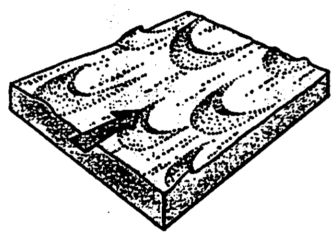
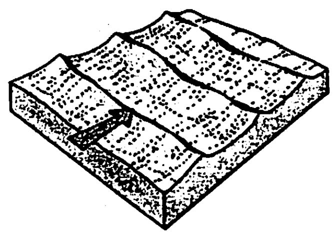
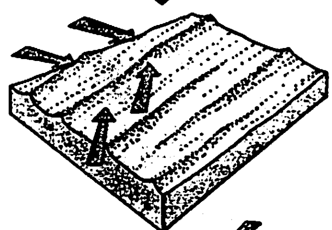
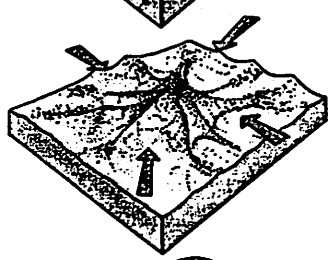
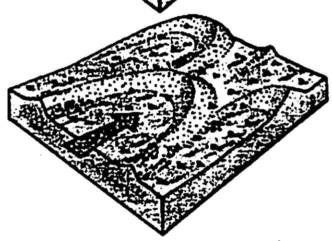
The Desert Winds Project--location, Jornada Experimental Range

Eileen Haney

On the Earth's surface, dunes form only in areas where low precipitation, a sediment source, and high winds favor the accumulation of sand-sized sediment. The absence of any of these factors means that dunes cannot form--however, increased precipitation can result in vegetated, stabilized dunes which indicate a dryer climate in the recent past.

Dunes come in many different shapes. Dune shape is controlled by wind speed and direction, sediment supply and vegetation. Five common dune types are illustrated in figure 1 (from The Dynamic Earth, Skinner and Porter). We will see examples of parabolic and barchan (or barcan) dunes at White Sands.

TABLE 12.1 Principal Types of Dunes Based on Form

Dune Type	Definition and Occurrence	
Barchan dune	A crescent-shaped dune with horns pointing downwind; occurs on hard, flat desert floors in areas of constant wind direction and limited sand supply; height 1 m to more than 30 m	
Transverse dune	A dune forming an asymmetrical ridge transverse to strongest wind direction; occurs in areas with abundant sand; can form by merging of individual barchans	
Linear dune	A long, relatively straight, ridge-shaped dune in deserts with limited sand supply and variable (bidirectional) winds; slip faces change orientation as wind shifts direction	
Star dune	An isolated hill of sand having a base that resembles a star in plan; sinuous arms of dune converge to form central peak as high as 300 m; tends to remain fixed in place in areas where wind blows from all directions	
Parabolic dune	A dune shaped like a U or V, with open end facing upwind; trailing arms, generally stabilized by vegetation, also point upwind; common in coastal dune fields; some form by piling of sand along lee and lateral margins of deflated areas in older dunes	

The interior of dunes changes according to the dune shape, but the following cross-section (figure 2) illustrates the basics of a medium-sized dune in cross-section. When dunes are preserved in the rock record, the cross-beds are often spectacular.

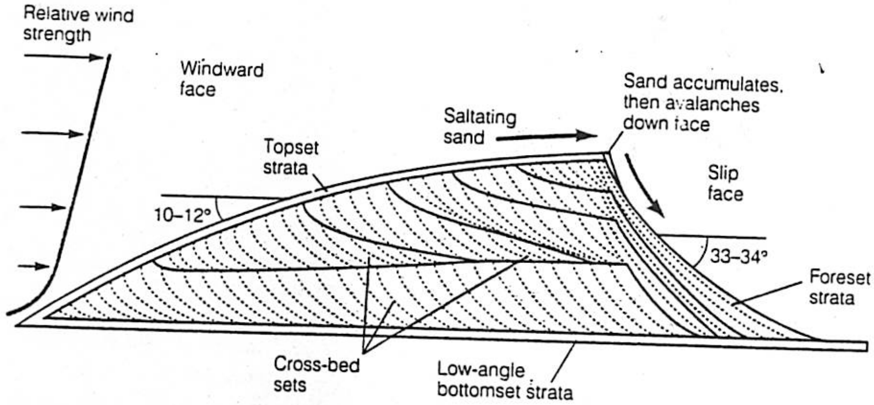


FIGURE 12.15 Cross section through a barchan dune showing typical gentle windward slope and steep slip face. Thin topset strata overlie sets of cross-bedded strata representing old slip faces. Sand grains saltating up the windward slope fall onto the top of the slip face where they accumulate before avalanching downward to produce foreset strata resting at the angle of repose.

Sand is too heavy to fly through the air. Therefore, it moves through a process called saltation. Smaller grains are entrained in the air. See figures 3 and 4.

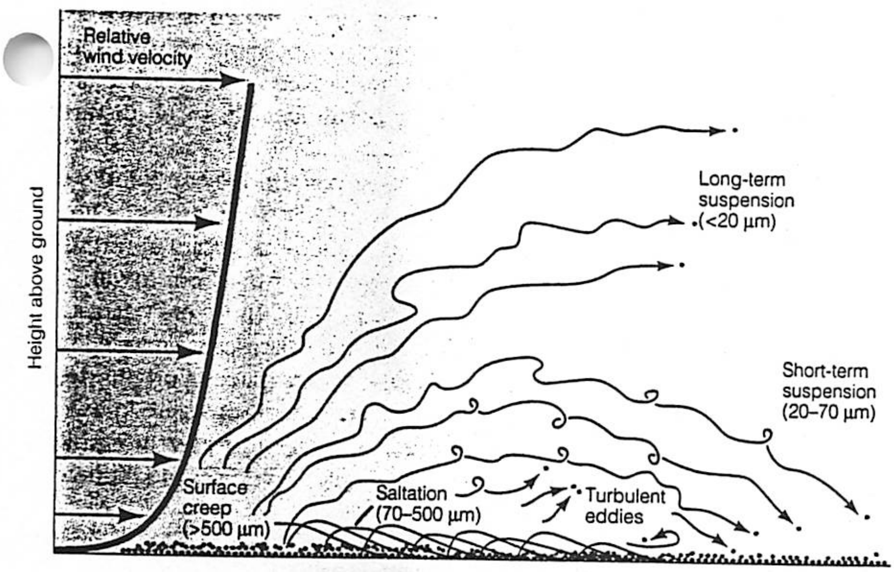


FIGURE 12.3 Under conditions of moderate wind, sand grains larger than 500 μm (0.5 mm) in diameter move by surface creep, while smaller grains (70–500 μm) saltate across the ground surface. Still finer particles (20–70 μm) are carried aloft in turbulent eddies and encounter faster moving air that transports them downwind as they slowly settle to the ground. The finest dust (less than 20 μm) reaches greater heights and is swept along in suspension as long as the wind is blowing.

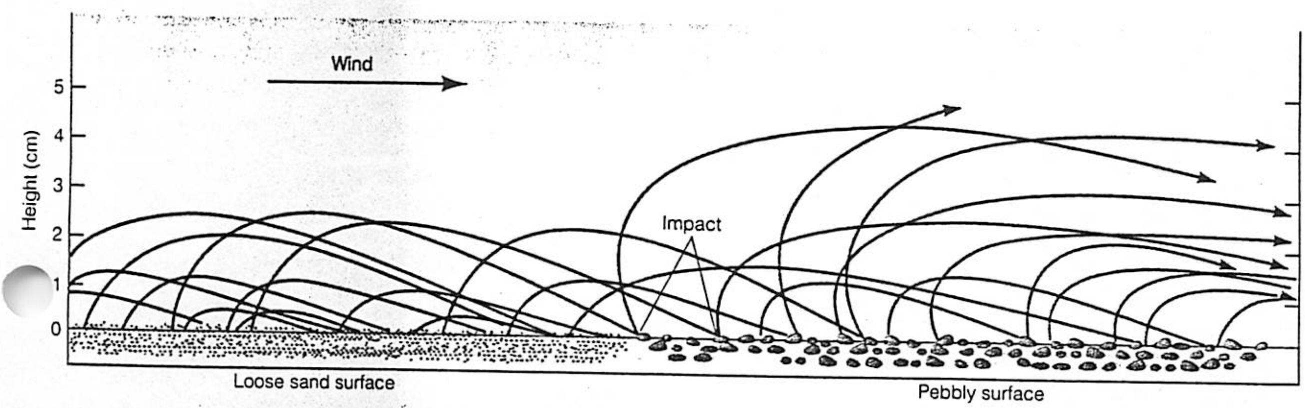


FIGURE 12.4 Strong wind causes movement of sand grains by saltation. Impacted grains bounce into the air and are carried along by the wind as gravity pulls them back to the land surface where they impact other particles, repeating the process.

The Desert Winds Project--location, Jornada Experimental Range

We will not be able to actually drive in to see the GeoMet station at the Jornada Experimental Range. However, we can stop along the road and briefly discuss this project. In short, the USGS in Flagstaff has a researcher who is maintaining a series of meteorological stations that measure wind speed, sand flux, precipitation, etc. at seven locations in dune fields throughout the southwest. Current research shows that dune formation is primarily controlled by local storm regimes, and that predicting sand movement based on average wind speeds and sand size is iffy at best. Instead, factors and 'dry' wind speed and velocity, which I define as the speed and velocity of winds unaccompanied by or preceeding a storm, are most effective at moving sand.

The Jornada area contains dunes that are fairly well stabilized by vegetation. We should be able to compare/contrast dunes from White Sands with those in Jornada.

Implications for planetary science.

Dunes form only where sediment of appropriate size is available. Wind (or water) speeds must be high enough to begin and maintain saltation. Therefore, dunes can only form in the presence of a fluid and particles of rock. (On earth, water is the best eroder of rock into sand-sized grains.) The morphology of dunes is also controlled by vegetation or other barriers to fluid flow--therefore, dune morphology alone gives us some idea of the characteristics of the planet's surface.

River Terraces in the Rift Valley of the Big Rio Grande River

(no shadow of death here, unfortunately)

Sung off-key by Cynthia Phillips

<whine> "Mommy, what's a river terrace?" </whine>

"Well, dear,
listen my child, and I'll tell you a story
and don't you worry, 'cause it won't be gory
It's about a river, in a big rift valley
(it's got nothing to do with comet Halley)

See a long time ago, when New Mexico was wetter
'twas a bit colder then, which might have been better
There were some glaciers up north, on top of the mountains
and when it warmed up, they melted like fountains

And the water flowed down, and the valley was a river
(it was probably cold, would have made you shiver)
And as it flowed, it deposited some sediment
(and covered over what we know is a pediment)

So this sand and rock began to form a flood plain
This was a long time ago, but we know it the same
Then it warmed up some more, and the river ran faster
So it carved up the valley, just like a sand blaster

And it ate through the flood plain, and made itself a channel
If we'd been there at the time, we would have worn flannel
But of course it couldn't cut through the whole flood plain
So it left some shoulders -- terraces are their names.

As time went on, it continued in this cycle
And the results you'll see, if you try to take a hike-l
The top terraces are the oldest, and the bottom are the youngest
(if you hike, make sure to check your toes for fungus)

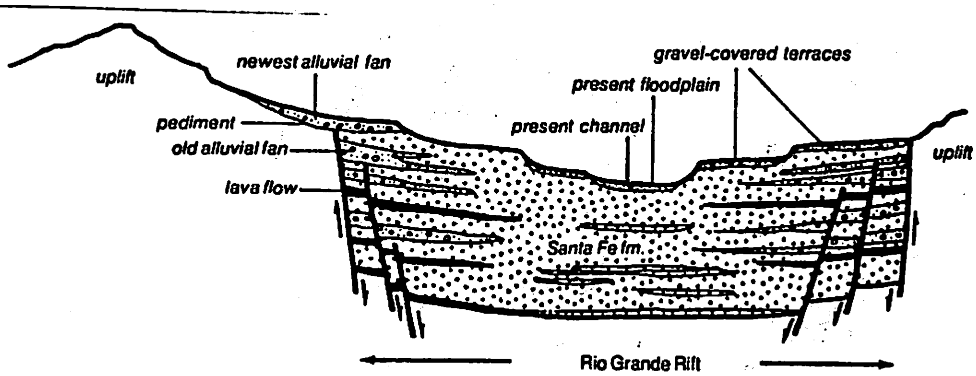
So remember that today, during times of low discharge,
the Rio Grande runs slowly, and deposits sand bars
But when the volume increases, and the speed gets insane
Then the river will cut into its own flood plains.

The river terraces in the Rio Grande Rift Valley are evidence of the large role water played in the development of the landscape. River terraces are broad, gravelly features that stairstep the edges of many valleys. These were once the floodplains of rivers, and were then cut into by the very rivers which created them.

The river terraces in the Rio Grande Valley were created in response to the fluctuating climates of the Ice Ages. During this period, small mountain glaciers developed in parts of Northern New Mexico, and other areas received much more rain than they do today. Floods were common, with rainy cycles reflecting the advances of ice far to the North.

During this time, the rivers alternately deposited and cut down through thick layers of sand, gravel, and silt, leaving fragments of old flood plains as terraces along the borders. The terraces thus represent a balance between deposition of sediments and downward erosion. During times of increased river discharge, corresponding to glacial episodes far to the North, major valleys were carved. During drier episodes, corresponding to interglacial stages, erosion and sedimentation both increased as the climate became more arid, and thus had less vegetation to hold down soils.

The uppermost terraces are the oldest, remnants of the initial flood plain. As time goes on, renewed erosion cuts new channels, which later fill in with river flood plain deposits that will end up as lower terraces. See the diagram below for a cross-section of the rift.



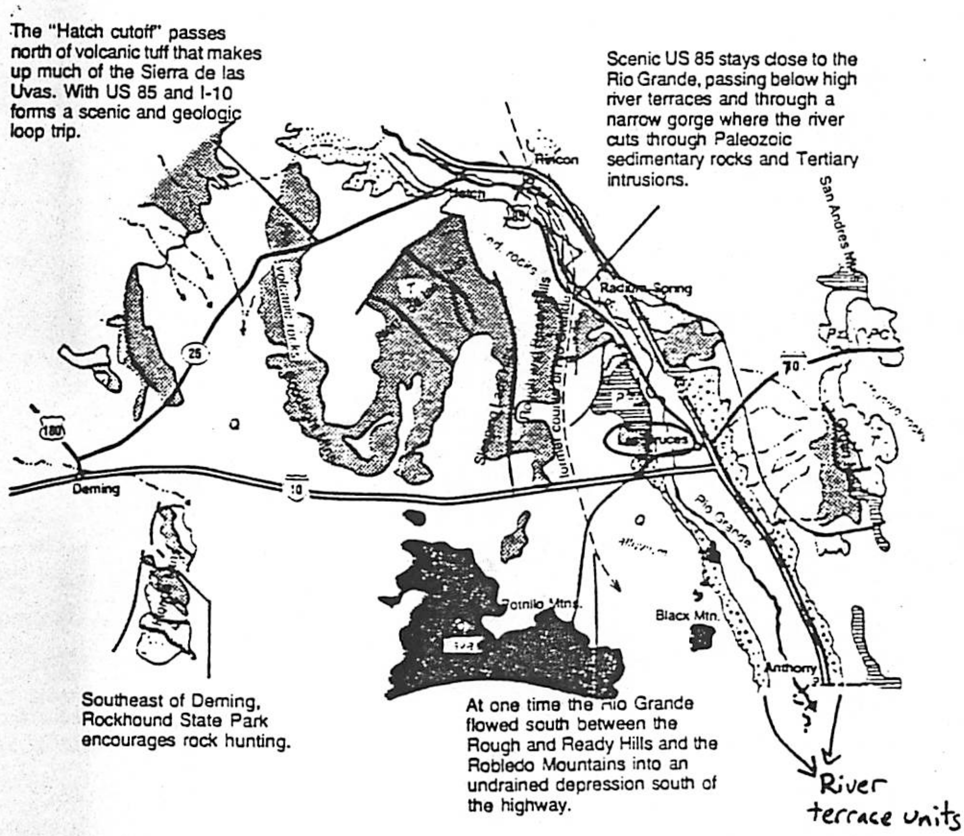
In cross-section, the Rio Grande Rift is filled with sand, silt, gravel, clay, lava, and ash flows of the Santa Fe group, thinly covered with younger terrace deposits.

Thus, in alternating cycles of deposition and downcutting, the Rio Grande filled in the rift valley with sand and gravel brought in from adjacent mountains and from upstream, and then cut into it, alternately building and trenching, to create a series of steplike terraces along its margins. This process continues today: during times of low discharge, the Rio Grande deposits gravel bars and sand bars, and with increasing discharge, it cuts into established floodplains.

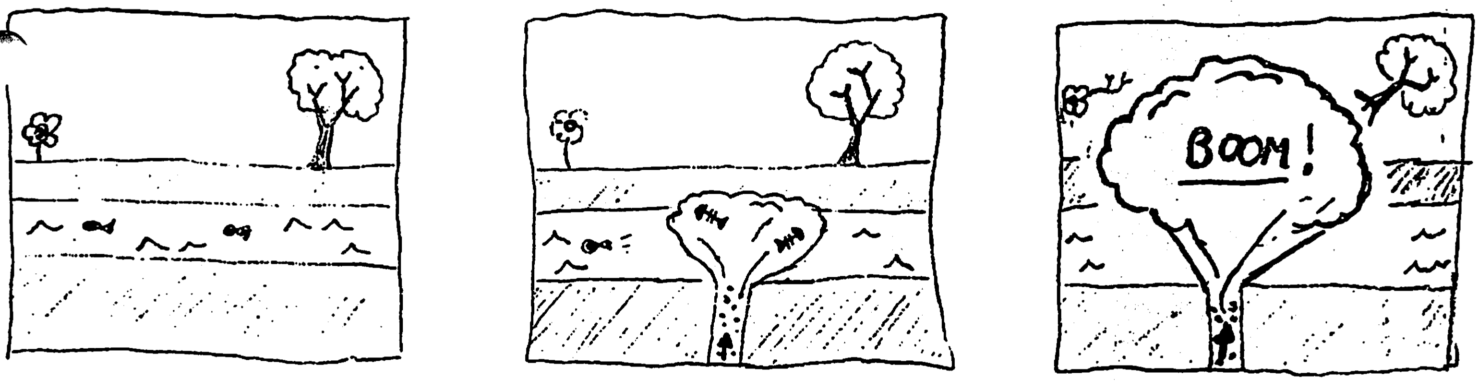
Geologically, the tertiary terrace deposits are part of the Santa Fe group. This unit varies from place to place due to differing sources of sediment, and different kinds of lava flows and volcanic ash which flowed into or blew onto it. These sediments are mostly soft and easily eroded, and are tilted in some areas by rift valley faults. If they contain lots of volcanic ash, they erode into badlands.

Most of the town of Las Cruces is built on the flood plain and terraces of the Rio Grande. Highway I-10 drops down over several terrace levels to the river floodplain, then climbs through their counterparts on the other side of the river. The sediments that make up these terraces can be seen in roadcuts and gravel pits along US 70. The Sante Fe group in this area consists mostly of old alluvial fans interlayered with river sediments. In places, the Santa Fe sediments contain the fossilized bones of mammoths, mastodons, horses, and camels that lived in the area between 10 million and 500,000 years ago. The porous gravels also act as aquifers for the water wells of the city of Las Cruces.

In the geologic map below, the river terrace deposits can be seen as the dotted unit lining both banks of the Rio Grande in the Las Cruces area.



Some of the information in this handout was brought to you by the letter R, the number 32, and Roadside Geology of New Mexico, by Halka Chronic.



MAAR VOLCANOES:

magma-ground-water interaction
(don't necessarily need much water!)

simple, circular <u>hole</u> in the ground
(below surface feature)

since holes in ground,
often fill with water and are lakes

low rims of ejecta

diameter: km's
depth: 100's meters

magma material can be
glassy, non-vesiculated, blocky
(quenched quickly and then exploded)

References: Fisher and Schmincke, Pyroclastic Rocks, 1984.
Francis, Volcanoes - a Planetary Perspective, 1993.

An **explosion crater** is the hole <u>below</u> the ground. **Tuff rings** and **tuff cones** are similar but form features which rise <u>above</u> the ground. Differences are thought to be due to **water:magma ratios.**

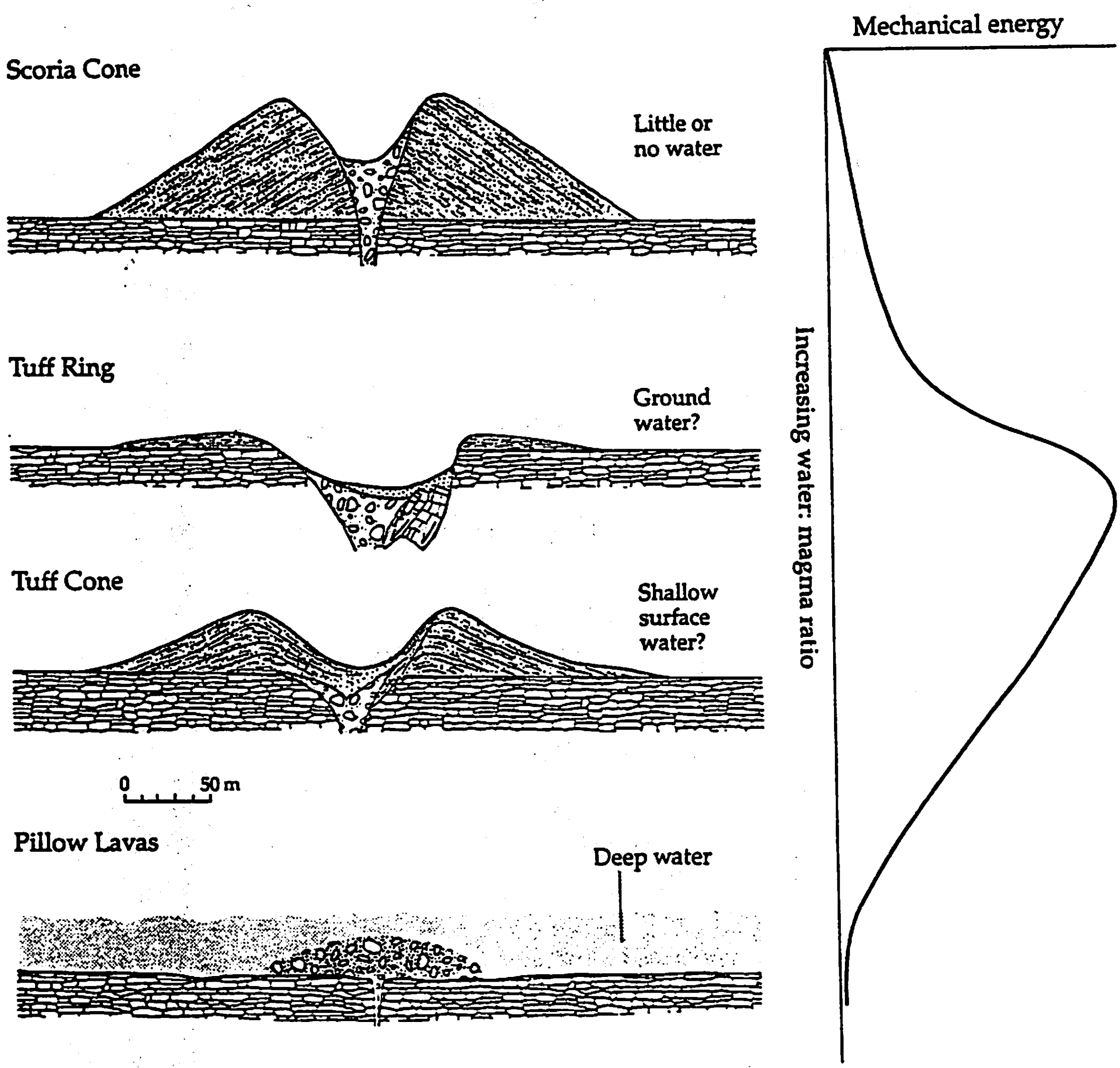


Fig. 16.8 Effect of increasing amounts of water on morphology of small basaltic volcanic constructs. Internal structures are shown only schematically: slumps from steep crater walls are observed in some tuff rings, while inward and outward dips are characteristic of tuff cones. After Wohletz, K. H. and Sheridan, M. F. (1983). Hydrovolcanic explosions II. Evolution of basaltic tuff rings and tuff cones. *Am. J. Sci.* **283**, 385–413.

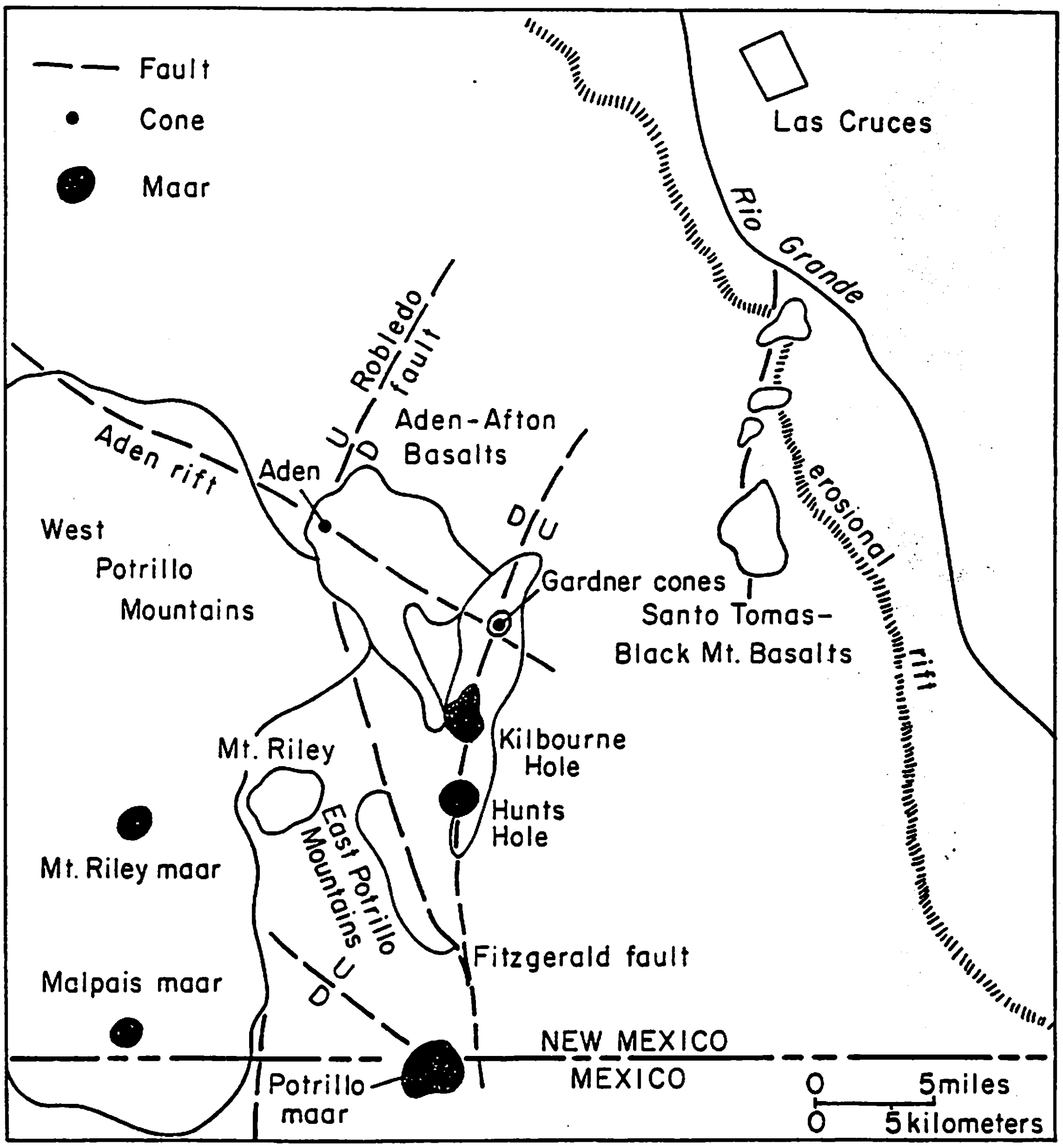
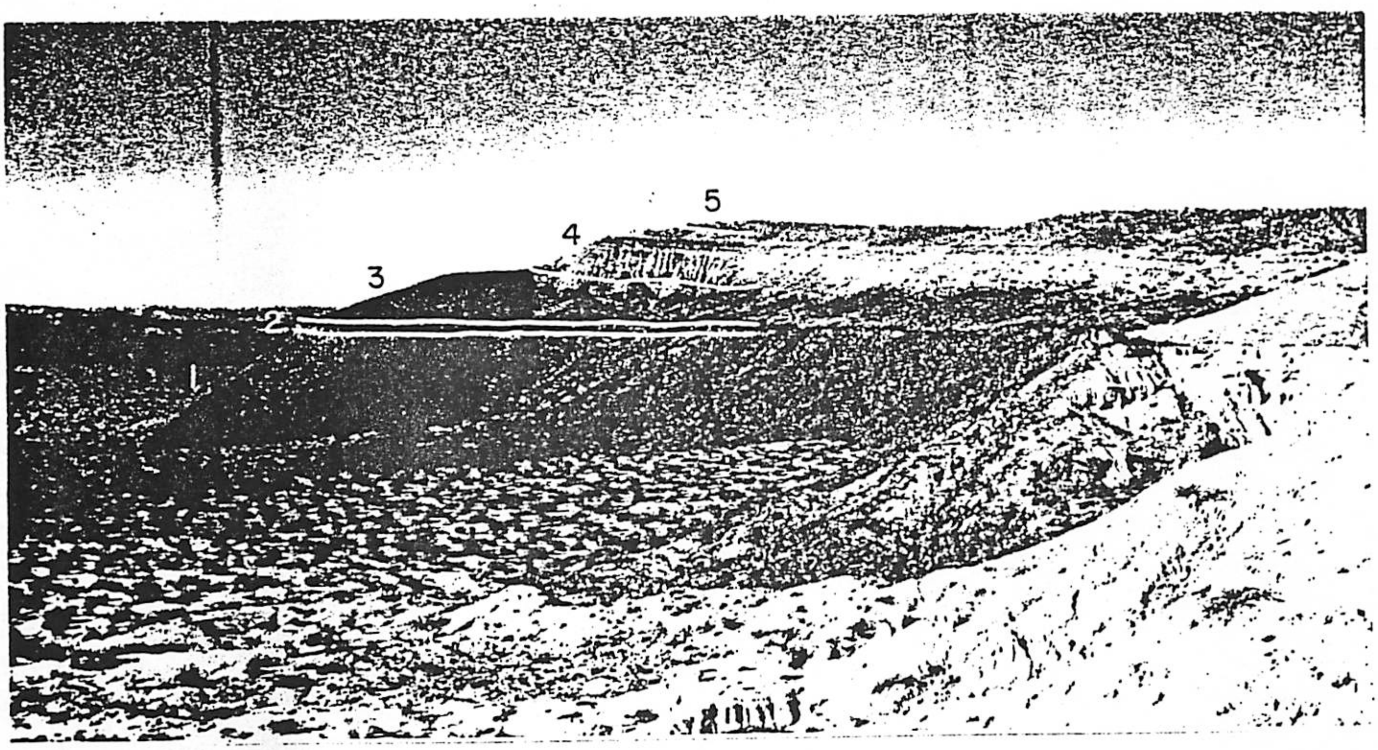


FIGURE 1—INDEX MAP OF THE POTRILLO BASALT FIELD.

YOU ARE HERE:

map of area showing locations of maar volcanism.

(figure from Hoffer, Geology of Potrillo Basalt Field, South-Central New Mexico, New Mexico Bureau of Mines and Mineral Resources, 1976)



Kilbourne Hole:
(photo from Hoffer, 1976)

1) Santa Fe Group: sand, silt, clay; 1.6 mya

2) Basalt Flow: dense porphyritic olivine basalt

3) Coarse Ejecta: bedded tuffs

4) Rim Volcanics: airfall and base surge origin

5) Blown Sand: Holocene

Xenoliths (xenoids, enclaves, noddies, lava gems, olivine bombs, chrysolite fragments, basic secretions, inclusions, enclosures, or "The Poor Man's MOHO") at Kilbourne Hole **Kevin Righter**

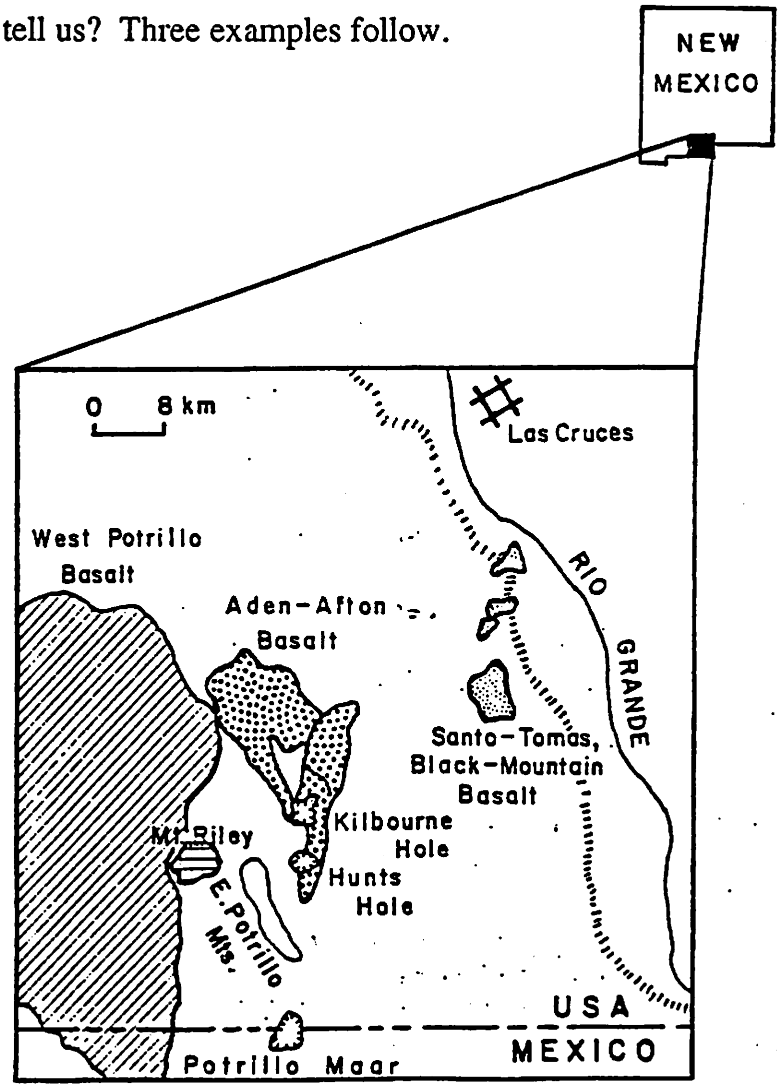
Kilbourne Hole is a maar volcano in the late Pleistocene Potrillo volcanic field in south-central New Mexico, within the Rio Grande depression. The Potrillo volcanic field includes three main areas: the Santo-Tomas Black Mountain basalt field in the east, the central region with the Kilbourne Hole, Hunts Hole and Potrillo maar volcanoes, and the basalt and rhyolite of the Potrillo Mtns. in the east (Fig. 1). This volcanism is accompanied by extensional faulting that defines the Rio Grande Rift system (Fig. 2).

Kilbourne Hole is famous for the diversity of xenoliths that are found within its volcanic deposits. A xenolith (xeno = "foreign" and lith = "rock") is a chunk of rock that is found within intrusive (plutonic) or extrusive (volcanic) igneous rocks. Although there are many volcanic vents within the SW United States where xenoliths can be found, the Kilbourne Hole samples exhibit the widest range of rock types, including both mantle and deep crustal types. The following types occur here:

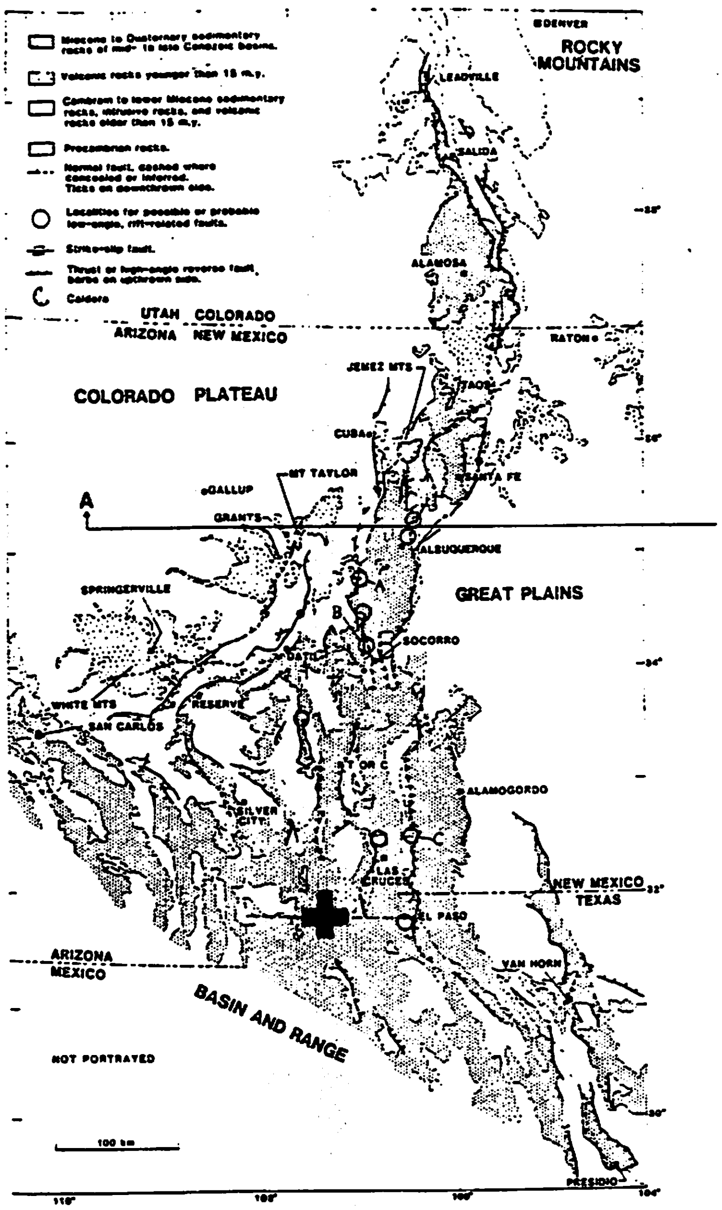
a) Ultramafic: spinel lherzolites and pyroxenites; composite lherzolite and pyroxenite xenoliths
b) Mafic: garnet orthopyroxenites, two-pyroxene granulites
c) Feldspathic: garnet-and sillimanite-bearing granulites, charnockites and anorthosites.

Rock names are given on the basis of mineral proportions and textures (Figs. 3)

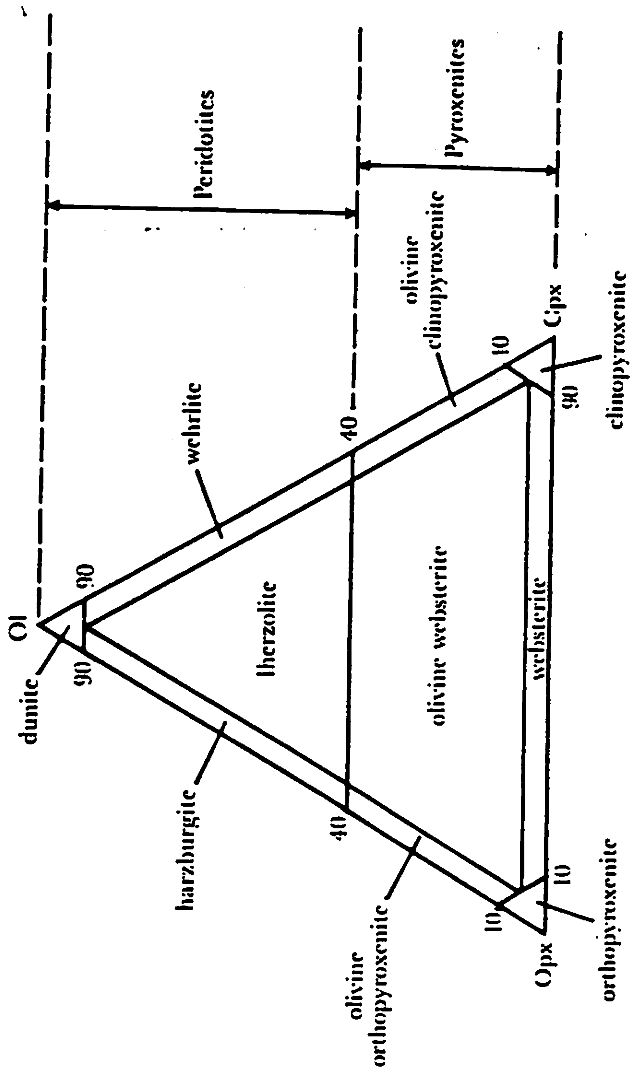
What can they tell us? Three examples follow.



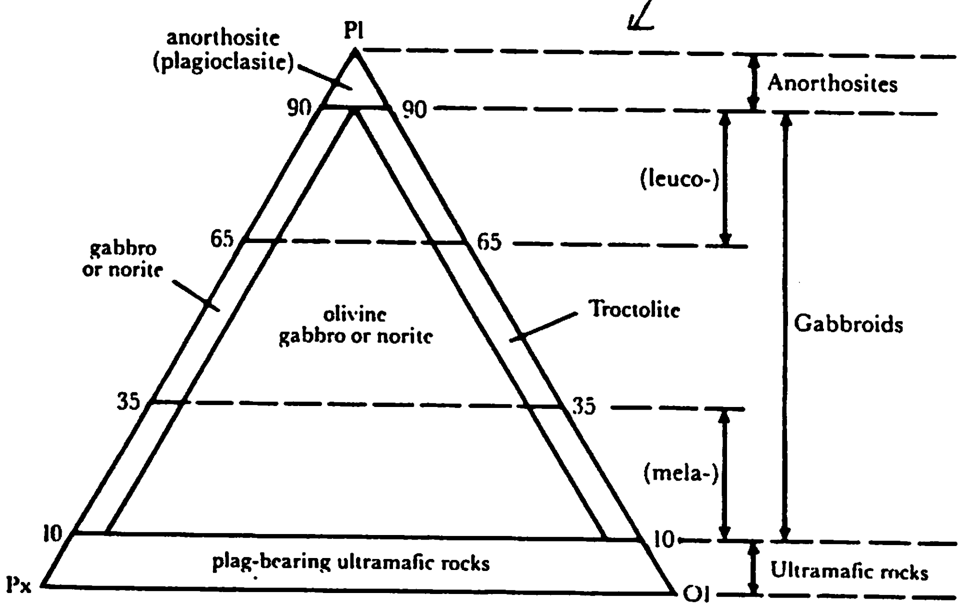
from Padovani and Carter (1977)



from Olsen et al. (1987)
Figure 2



Figs. 3



1) Terrestrial accretion models: primitive material from the upper mantle can help to constrain models for the early history and accretion of the Earth. Al/Si vs. Mg/Si of fertile peridotite (Fig. 4); also siderophile element concentrations in fertile peridotites constrain core formation models.

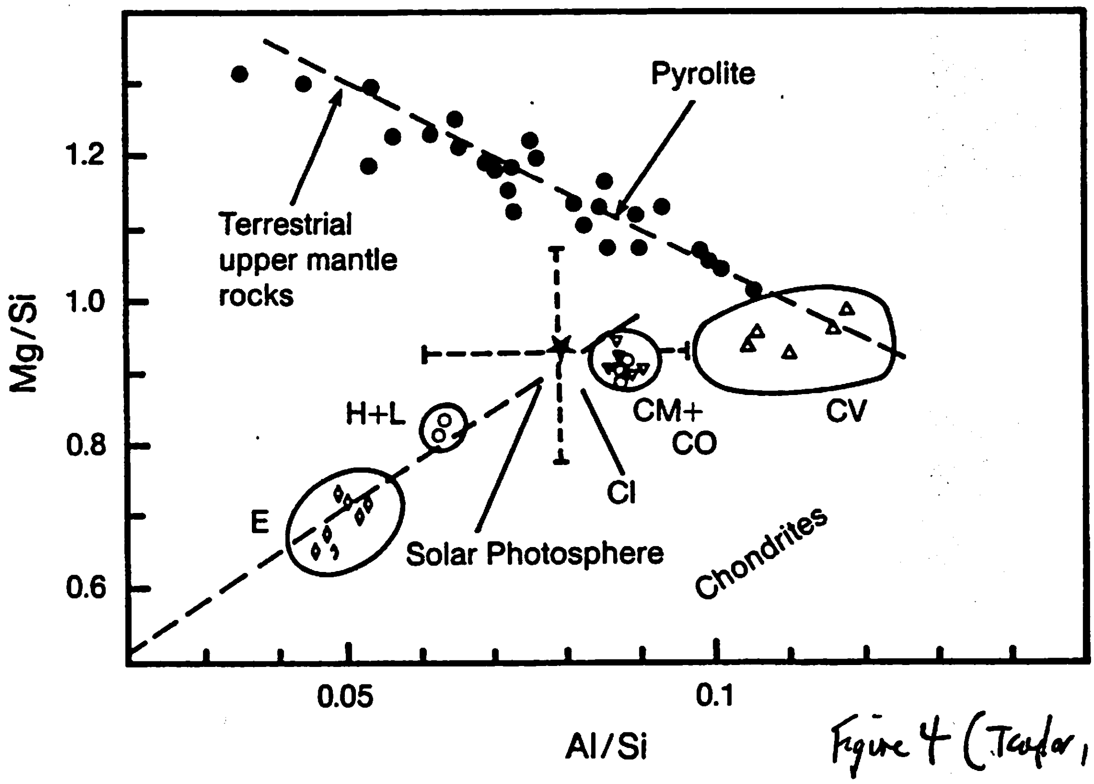


Figure 4 (Taylor, 1992)

2) P-T estimates and the lithosphere: how do we know that these samples come from great depth? Quantification of mineral equilibria - experimental studies and thermodynamic calculations (Fig. 5: P-T diagram with estimates and examples of types of equilibria used). Petrologic studies of the mantle and crustal nodules can be linked with seismic data to produce models for the lithosphere in this region (Fig. 6: McGetchin and Smyth, 1973; P-T diagram and cross-sections).

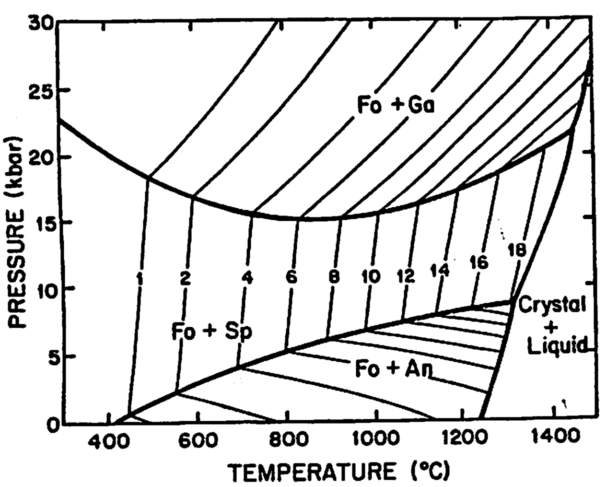


Figure 3 Phase relationships in the CMAS system, modified from Gasparik (1984). Heavy lines indicate univariant reactions; light lines (numerated) indicate the Al content of clinopyroxene.

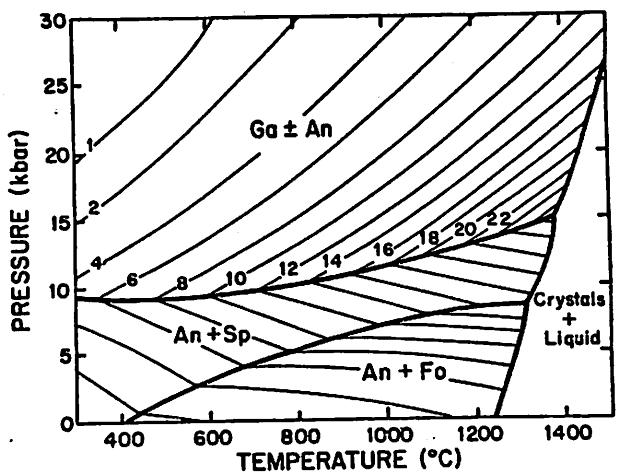


Figure 4 Phase relationships in the CMAS system, modified from Gasparik (1984). H lines indicate univariant reactions; light lines (numerated) indicate the Al content of c pyroxene in plagioclase-dominated assemblages.

Figure 5: Bohlen and Lindsley (1987)

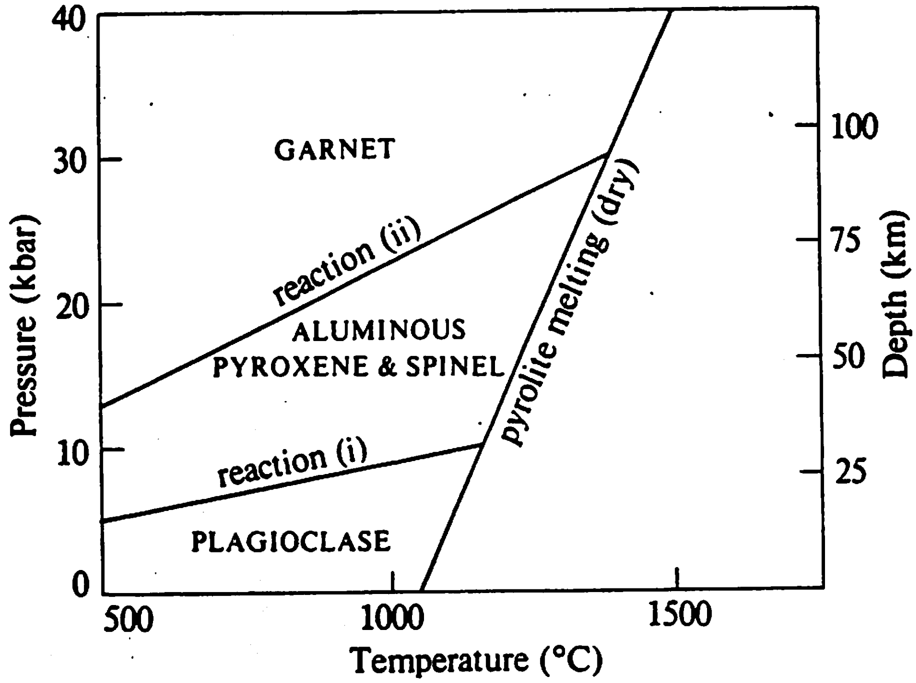


Fig. 5: Brown + Mussett (198

(i) olivine + feldspar → clinopyroxene + orthopyroxene + spinel

(ii) clinopyroxene + orthopyroxene + spinel + more feldspar → garnet

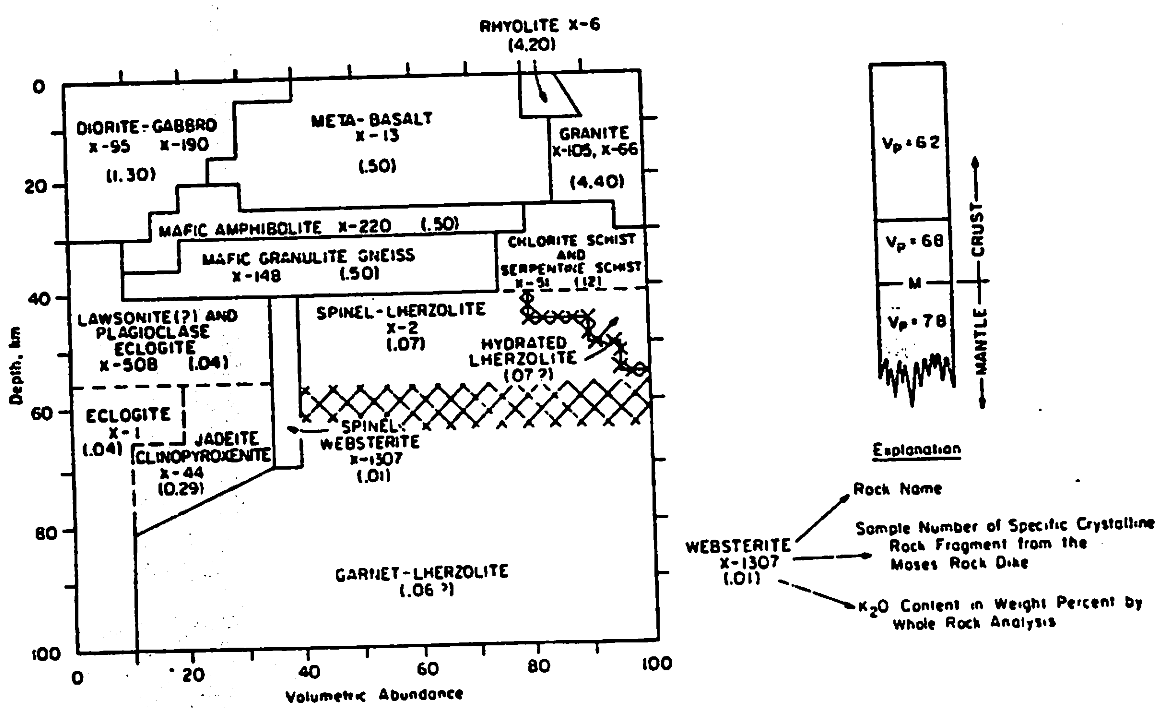


Figure 6: McGetchin and Smyth (1973)

3) Magma ascent rates: Nodule size and density, together with host magma characteristics allow estimates of ascent rate of these types of eruptions.

The velocity of magma ascent through the lithosphere can be estimated using the equation for Stokes Flow of a solid body through a liquid:

$$U = \left[\frac{8}{3} \frac{ag(\rho_f - \rho_s)}{c_D \rho_f} \right]^{1/2}$$

Equation 6-230 in Turcotte and Schubert, 1982

where
U is the upward velocity of the fluid
a is the xenolith radius (0.15 m is typical)
g is the gravitational constant (9.8 m/s^2)
ρ_f is the fluid density (2700 kg/m^3)
ρ_s is the solid density (3300 kg/m^3)
c_D is the drag coefficient (determined independently; 0.34)

Given the above values, one calculates that U = 0.87 m/s, indicating that magma can traverse the entire lithospheric thickness (~100 km) in about 32 hrs!

References:

Bohlen, S.R. anbd Lindsley, D.L. (1987) Thermometry and Barometry of igneous and metamorphic rocks. Ann. Rev. Earth Planet. Sci. 15, 397-420.
Brown, G.C. and Mussett, A.E. (1981) The Inacessible Earth. George Allen and Unwin, London.
McGetchin, T.R. and Smyth, L.T. (1973) A crustal-upper mantle model for the Colorado Plateau based on observations of crystalline rock fragments in the Moses Rock Dike. Jour. Geophys. Res. 77, 7022-7037.
Olsen, K.H., Baldridge, W.S., and Callender, J.F. (1987) Rio Grande Rift: an overview. Tectonophysics 143, 119-139.
Padovani, E.R. and Carter, J.L. (1977) Aspects of the deep crustal evolution beneath south central New Mexico. In The Earth's Crust (ed. J.G. Heacock), pp. 19-55, Amer. Geophys. Union.
Roden, M.F., Irving, A.J. and Murthy, V.R. (1988) Isotopic and trace element composition of the upper mantle beneath a young continental rift: Results from Kilbourne Hole, New Mexico. Geochim. Cosmochim. Acta 52, 461-473.
Taylor, S.R. (1992) Solar System Evolution. Cambridge University Press, New York.
Turcotte, D.L. and Schubert, G. (1982) Geodynamics. Academic Press, New York.

LPL Field Trip Report

Ash-flow tuffs of the Chiricahuas

by A. McEwen

At the stop chosen by Jennifer to talk about hodoos, I will talk about ash-flow tuffs in general and in the Chiricahuas.

Now it's time for that amazing game show...

Hoodoos!

With your Hostess with Neurosis, Jennifer Grier

What is a Hoodoo?

A hoodoo or rock chimney is a column, spire, balanced rock column or totem pole formation formed by erosion along joints in some igneous and sedimentary rocks.

So What Did You Say Was Responsible for Hoodoos?

A fracture or crack in a rock along which there has been no movement is called a joint. Joints can be found on all scales in igneous and sedimentary rocks. They often occur in sets of parallel or intersecting patterns. These patterns are due to failure along local stress directions in the rock. In the case of the igneous rocks seen in the Chiricauas, the joints have no doubt developed due to stresses associated with the cooling and contraction of the rock. The erosion of these rocks is controlled by the strong orientation of the joints, since that is where the rock is most vulnerable to disintegration and removal.

The hoodoos (or rock chimneys) are formed by the erosion of rocks along strong patterns of these steeply dipping (near vertical) joints. Erosion along joints is responsible for the hoodoos found in Bryce Canyon National Park, and columnar jointing is also responsible for the Devil's Postpile formation in the Devil's Postpile National Monument.

What About the Hoodoos in the Chiricahua's Specifically?

The geology of the Chiricahua Mountains area is dominated by volcanic events associated with the Turkey Creek Caldera. Several regimes of volcanic activity with associated ash flows have affected the region. Specifically, about 25 Ma ago, a series of eight individual ash flows/cooling units were laid down which have a total thickness of almost 2000 ft. Within each of these units some of the volcanic products came down rapidly, clearly very hot, and fused almost immediately into rock forming hard welded tuff. Some of the volcanic products were produced by ash that fell from high rising ash clouds, which being cooler thus fused more slowly, and produced a more poorly consolidated tuff layer.

The hoodoos here are predominantly located in a single cooling unit about 880 ft thick. Because of the particular cooling and contraction history of the welded tuff, it developed steeply (near vertical) dipping joints, along which subsequent wind and water eroded away the rock. This is responsible for the "totem pole" type hoodoos seen all over the monument. The fact that harder layers of rock are interspersed with softer layers causes the formation of balanced rocks and hourglass shaped formations as the softer layers are preferentially eroded away.

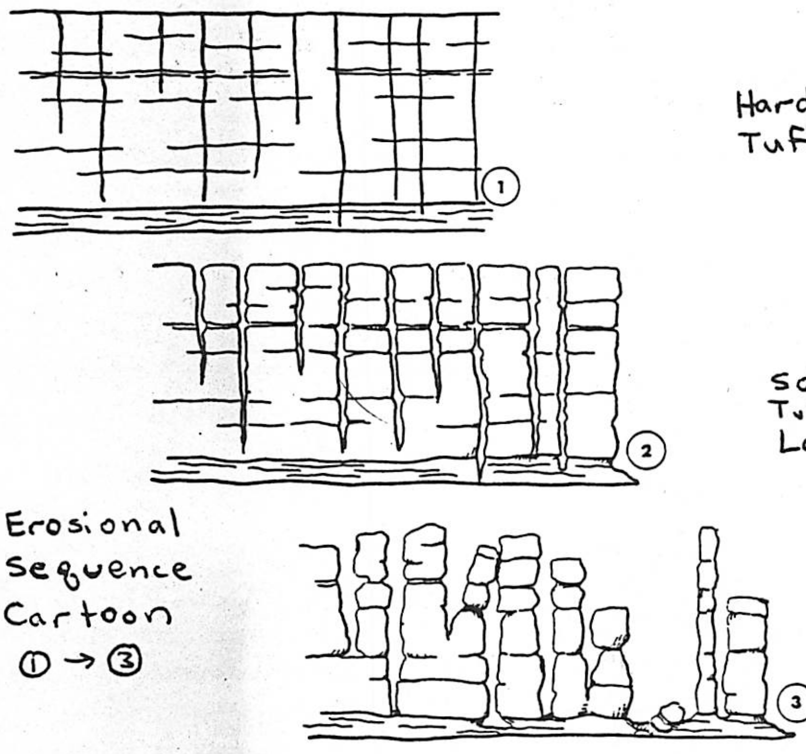
Why Don't Those Balanced Rocks Just Topple Over?

The hoodoos and rock columns, especially the balanced rocks, appear as though they should be unstable under their own static load of rock mass, or certainly under any amount of seismic shaking. Yet, finite element stress modeling appears to indicate otherwise. Modeling was done on columns with particularly precarious appearing geometries like asymmetrical overhang, narrow aspect, and severely incut hourglass shapes. The modeling included compressional and tensile failure strength and the coefficient of static friction for slip along the joints. None of the columns appeared to be close to either compressional or tensile failure, therefore failure along unjointed rock was shown to be unikely to occur. The modeling seems to indicate that slip along the joints is the most likely mode of failure, which again shows the importance of the joints in forming these rock formations. It turns out that this means the columns with hourglass or balanced rock morphologies can be more stable than the cylindrical columns, because slip along the vertical joints is more likely than along the horizontal "weak" rock zones, or any horizontal jointing.

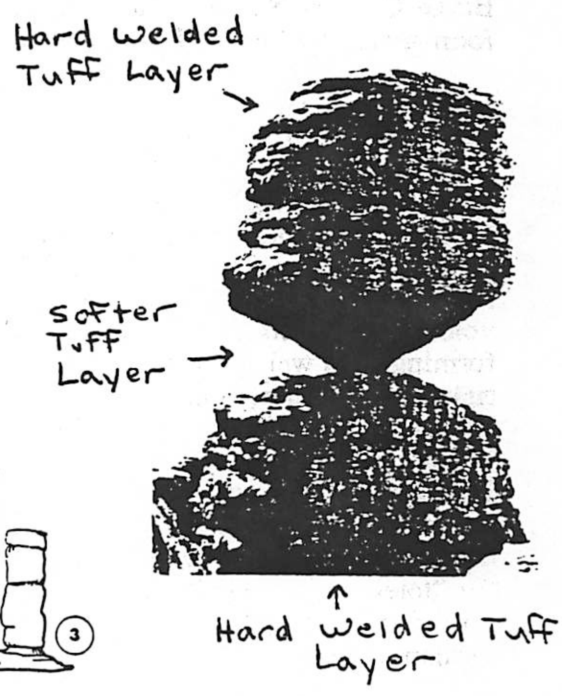
The vertical erosion rate of the hoodos has been determined to be 1.7 cm every 1000 yrs. Since the typical column height is about 40 m high, this seems to indicate that the columns began to be formed about 2.4 Ma ago. Also, the uniformity of the heights of most of the columns and the presence of benches in the topography may indicate a major seismic event which at that time wiped out the previous generation of columns. It would have to be a very major event, since a 7.2 magnitude earthquake only 120 km away in 1887 did not noticeably affect the columns.

Besides Making Pretty Hoodos, Why Should We Care About Joints?

Joints are also of great importance in the circulation of a wide range of fluids, including, rain, groundwater, oil, gas, and mineralizing solutions. This circulation of fluids along joints is often responsible for the shapes and orientations of rooms and passageways in caves. In limestone caves, this shaping is caused by the selective solution removal of limestone along joint trends. An example of this is the Left Hand Tunnel of **Carlsbad Caverns**, which is elongate parallel to the predominant set of joints that are cutting the limestone in that part of the cavern. The tall, narrow passages here are centered on prominent vertical joints that once guided the circulation of groundwater.



Erosional Sequence Cartoon ① → ③



The Places I Got My Info etc.:

Geodynamics, Aplications of Continum Physics to Geol. Problems, Turcotte and Schubert, 1982, John Wiley and Sons.
Jagnow, 1979 Cavern Development in the Guadalupe Mountains: Adobe Press, Albuqureque, New Mexico, 55p.
Structural Geology of Rocks and Regions, George H. Davis.1984, John Wiley and Sons, Inc.
Roadside Geology of Arizona Halka Chronic1983, Mountain Press Publishing.
Hall, Douglas. Modelling failure of Nature Rock Columns. Paper Geomorpholgy, 15, 2, p 123-134, 1996.
Abstract Gelogical Society of America Abstracts and Programs., p A-460, 25, 1993.

The Planetary Connection

Eric Wegryn

As planetary scientists, we frequently ask the question on our geology field trips, "What's the planetary connection?" We study Earth to help us put what we learn about other planets into context, and in turn use the knowledge we gain about other worlds to help us understand our own planet.

The combination of geological features we see on this trip is obviously unique to this particular area of our planet, but each of these features in turn may be in some way relevant to the study of other planets. We can see dunes on Mars and Venus, and indeed expect to find them on any planet with a solid surface and a significant atmosphere (like Titan?); they can tell us about atmospheric flow directions and surface topography. The lava flow field near Carrizozo is certainly very relevant, as we see volcanic features on many other planets. And surely there are caverns on every planetary body (save perhaps giant gaseous planets like Jupiter).

But it is also clear that many of the features seen on this trip (as on most terrestrial field studies) are associated with liquid water. As we have seen, the caverns at Carlsbad (like most caves on Earth) were formed through the dissolution of limestone, which is itself formed at the bottom of oceans and seas (the Capitan reef and Guadalupe mountains are a prime example). Hoodoos are also caused by water erosion (although the joints that initiate them are not). The Rio Grande rift is a tectonic feature (the likes of which we might find on any large planet with enough internal heat), but the river terraces we see in it are obviously the result of water flowing through it. Maar volcanoes are volcanic features, but their particular nature is determined by the presence of water. And although dunes need only a sediment supply and a flowing fluid (*i.e.* wind) to form, sediment is a result of erosional processes, and its supply will be much more significant if liquid water is present. (Although wind erosion may produce a reasonable supply, as on Mars and Venus. Micrometeoroid erosion can produce regolith on airless bodies like the Moon, but this of course precludes the possibility of wind to produce dunes.)

So while we may see joints, faults, and tectonic rifts on other planets, as well as lava flows and other volcanic features, we do not expect to see them taken to the unique ends which we see here on Earth unless water is or has been present. To date of course we have evidence for liquid water only on Earth, although the signs are pretty clear that it existed in the past on Mars. It is thus perhaps fitting that the most relevant planetary connection for most of the features we see on this trip is with the planet we shall visit first. Hopefully it will not be too many years before geologists get a chance to explore the ancient river valleys and yet undiscovered caves of Mars.

And remember, even if we may not expect to find most of these geological features on any of the other planets of our solar system, there are of course other reasons for us to study them. As Andy Rivkin pointed out for example, the Castile evaporites are a wonderful example of a seasonal climactic record, and we may find similar analogs on other planets. So, while there may not be any interplanetary spelunkers any time soon, we can certainly become better planetary scientists by studying and understanding the geology of the world around us.