Lunar and Planetary Laboratory
Department of Planetary Sciences

FIRE AND ICE!!!!!!

(on Route 666)

PTYS 594a: Practicum

White Mountains (AZ)

26 - 28 April 1996

The University of Arizona
Tucson, Arizona

Table of Contents

(Not listed due to failure to comply with deadline : Jay's junk in the beginning)

PTYS 594a,

PLANETARY FIELD GEOLOGY PRACTICUM

Itinerary, White Mountains Trip 26-28 April 1996

H. J. Melosh, 353 Space Sciences, 621-2806

We will assemble at 7:30 am on Friday, 26 April at the LPL loading dock off Warren St. in five 4-wheel-drive Blazers. Try to be at LPL by 7:30 am to get the vans loaded. Please be sure that you have had breakfast beforehand, have ice for the coolers, etc. before we are scheduled to leave: Breakfast and ice runs just before departure have caused long delays in the past!

Our approximate itinerary is:

Friday, 26 April:

8:00 am	Distribute handouts, Depart LPL, turn right on Warren to 1st Avenue, then travel east to Cambell. Turn south to I-10, proceed east on I-10 to exit 289 at Marsh Station Road. Exit ramp crosses back over I-10, turn left (west) at the "T" intersection.
8:45 am	Turn right on dirt road; drive about 0.1 mi to the clay pit at the base of what is left of Cross Hill and park. We will observe and discuss the Cross Hill rock-avalanche.
9:30 am	Return to I-10 and proceed east to Texas Canyon rest stop, park vehicles at east end of parking lot. **Kirstin Girdner** will discuss the prominent spheroidal weathering at this site.
10:30 am	Continue east on I-10 to exit 352 and take Rte 666 (now 191) north toward Safford. After 14 miles turn left (west) on Rte. 366 and proceed to base of Mt. Graham mountain front. Park along road, where **Andy Freed** will describe how metamorphic core complexes are raised.
12:00 noon	Lunch
1:00 pm	Return to Rte. 191 and continue north through Safford. Turn right (east) on Rte. 70, travel 6 miles then turn left (north) on Rte 191. Continue through Clifton and Morenci, stop at the big open pit mine at Morenci. **Eric Wegryn** will describe the mine operations and the origin of porphyry copper deposits.
3:00 pm	Continue north on Rte. 191 through Sitgreaves National Forest toward Springerville.
5:00 pm	Turn left (west) on Rte. 260 at Eager. Proceed 8 miles west to Forest Service Road 560.
6:00 pm	Camp in vicinity of the small settlement of South Fork. Make Dinner, Fireside chat on the history of the Apache Nation by **Andy Rivkin.**

Saturday, 27 April:

8:00 am	Break Camp, return North on FR 560. Turn left (west) on Rte. 260 and travel 8 miles to the intersection of Forest Service Road 112. Turn left (south) and proceed to the sharp bend at Sheep Crossing. Park vehicles at the head of Mt.

	Baldy trail and prepare to hike toward the summit. Pack lunches and water. Be prepared for muddy trail conditions.
9:00 am	Begin hike up trail (about 8 miles round trip: we will **not** go all the way to the summit: to do this requires special permission from the Apache tribe, on whose reservation the peak lies). During the hikė seveal presentations will be made on the features along the trail. In approximate order:

The Sheep Crossing formation, by **Greg Hoppa**
Periglacial processes, by **Doug Dawson**
Glacial deposits, by **Zibi Turtle**
Glacial erosion, by **Barbara Cohen**
Glacial processes, from the earth to the universe, by **Ralph Lorenz**
Glacial history, White Mountains to the world, by **Karen Meyers** and **Cynthia Phillips**
Global climate cycles, by **David Trilling**
Habitable zones and stellar evolution, by **Rob Coker.**

5:00 pm	Return to vehicles, drive north on FR 112, turn right (east) on Rte 260. Proceed 3 miles to Forest Service Road 118, turn left (north). Continue about 1 mile to find a campsite. Camp, make dinner. Fireside chat by **Vince Converse** on UFO's ???!!!

Sunday, 28 April:

Asaad Antelope Hill (FR 558) For overlook of volcanic field. N. of Pinedale (FS overlook) (N. of McNary) — Head.

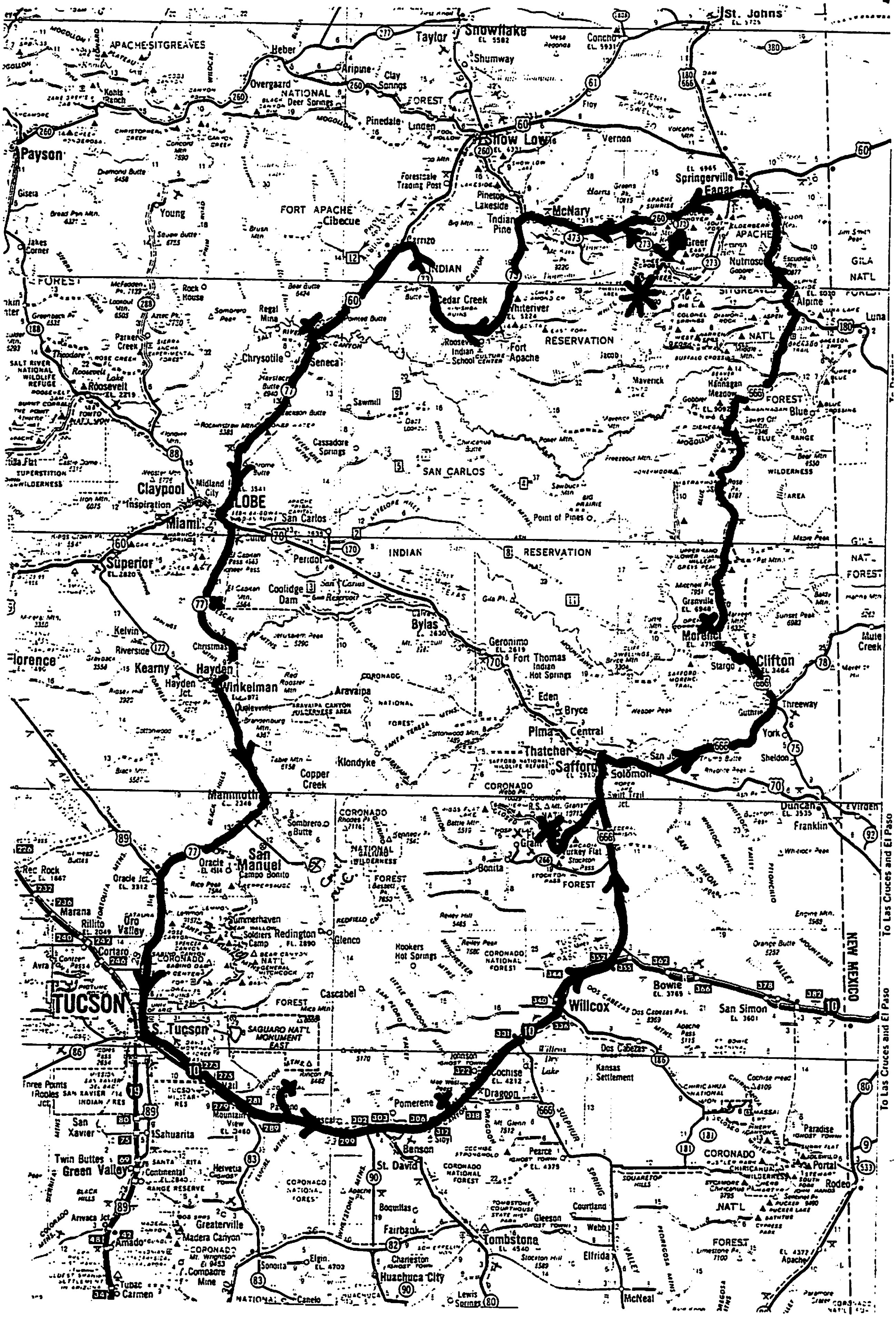
8:00 am	Break camp, return to Rte. 260 and proceed west toward McNary.
9:00 am	Stop at overlook on Mogollon rim near ~~McNary~~. Observe and discuss rim volcanism under the sage direction of **Jennifer Grier.**
9:45 am	Continue west on Rte. 260 to intersection with Rte. 73. Turn left (south) on Rte. 73 and continue through Whiteriver to Carrizo. This segment of the trip is entirely on the Fort Apache Indian Reservation.
12:00 noon	Lunch stop near Carrizo.
1:00 pm	Turn south on Rte. 60. Travel 10 miles south of intersection with Rte. 73 to milepost 308. Stop at outcrop of rim gravels for a presentation by **Jim Head** on the mechanisms of the Colorado Plateau uplift.
2:00 pm	Continue south on Rte. 60. Stop in Salt River canyon for a presentation on the geology of the canyon and the issue of intrusive vs. extrusive volcanism under the guidance of **Nancy Chabot** and **Bob Reid.**
3:00 pm	Continue south on Rte. 60. Optional stop may occur past milpost 279 to view outcrop of precambrian Barnes conglomerate.
4:00 pm	Arrive at Globe, turn left (east) on Rte. 70, proceed 3 miles to turn left (south) on Rte. 77. Another optional stop to see Barnes Conglomerate at milepost 158. Continue south on Rte 77 to just before milepost 153.
4:30 pm	Leave highway on small dirt road to north. Beware--visibility is limited and oncoming traffic moves fast here! Be careful! Stop to observe base of El Capitan rock avalanche.
5:30 pm	Return to Rte. 77 and continue south through Winkleman, Mammoth and Oracle to Tucson.
6:30 pm	Arrive Tucson, unpack and clean vans, go home.

Primary Drivers: Cohen, Converse, Freed, Reid, Wegryn

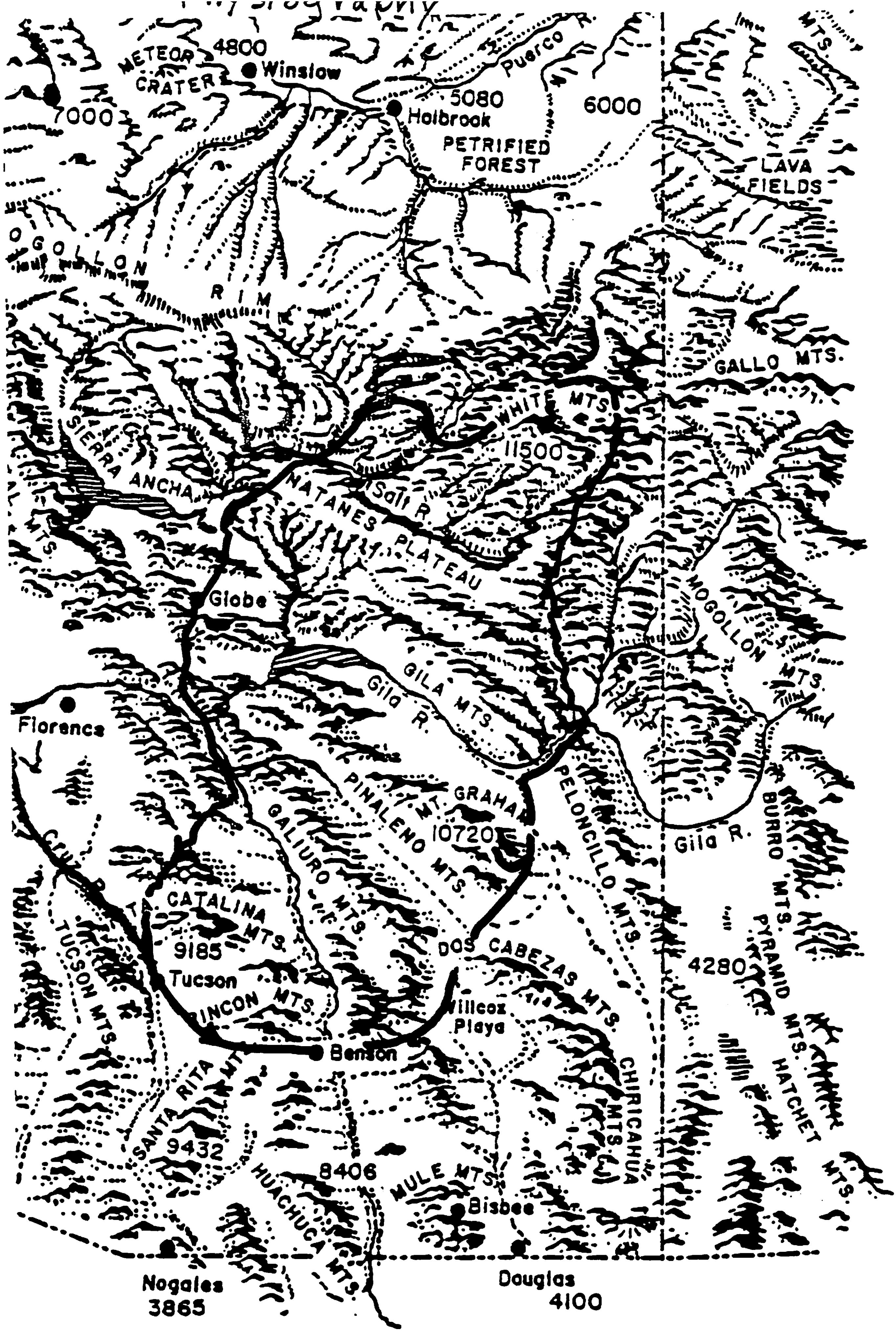
Participants:

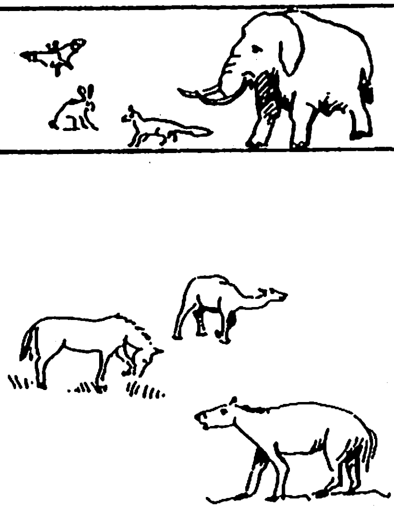
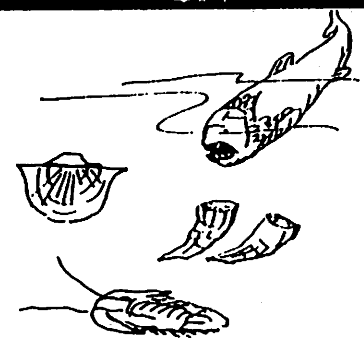
N. Chabot	B. Cohen
R. Coker	V. Converse
D. Dawson	A. Freed
K. Girdner	J. Grier
J. Head	G. Hoppa
D. Kring	R. Lorenz
K. Meyers	C. Phillips
R. Reid	A. Rivkin
D. Trilling	E. Turtle
E. Wegryn	

Road Map



St. Johns
Taylor
Snowflake
Shumway
Concho
Heber
Aripine
Clay Springs
Overgaard
NATIONAL
FOREST
Pinedale
Linden
Show Low
Vernon
Payson
Springerville
Eagar
Young
FORT APACHE
Cibecue
Forestdale Trading Post
Pinetop
Lakeside
Indian Pine
McNary
Greer
APACHE
Nutrioso
Carrizo
INDIAN
Cedar Creek
Whiteriver
Fort Apache
RESERVATION
Alpine
Luna
Roosevelt
Chrysotile
Seneca
Sawmill
Maverick
Hannagan Meadow
Blue
FOREST
Cassadore Springs
SAN CARLOS
Claypool
Inspiration
Miami
GLOBE
San Carlos
Point of Pines
Superior
Peridot
INDIAN
RESERVATION
Coolidge Dam
Bylas
Geronimo
Fort Thomas
Kelvin
Riverside
Florence
Kearny
Christmas
Hayden
Hayden Jct.
Winkelman
Aravaipa
Morenci
Clifton
Stargo
Eden
Bryce
Threeway
Guthrie
York
Sheldon
Pima
Central
Thatcher
Safford
Solomon
Klondyke
Copper Creek
Mammoth
Duncan
Virden
Franklin
San Manuel
Oracle
Oracle Jct.
Rec Rock
Marana
Rillito
Oro Valley
Cortaro
Avra
TUCSON
S. Tucson
Summerhaven
Redington
Soldiers Camp
Glenco
Bonita
Grant
Turkey Flat
Hookers Hot Springs
Cascabel
Willcox
Bowie
San Simon
NEW MEXICO
To Las Cruces and El Paso
SAGUARO NAT'L MONUMENT EAST
Three Points
Robles Jct.
San Xavier
Sahuarita
Mountain View
Vail
Pantano
Mescal
Pomerene
Benson
Johnson
Cochise
Dragoon
Dos Cabezas
Kansas Settlement
Paradise
Portal
Rodeo
Twin Buttes
Green Valley
Continental
Helvetia
St. David
Pearce
Arivaca Jct.
Amado
Greaterville
Madera Canyon
Boquillas
Fairbank
Tombstone
Gleeson
Courtland
Webb
Elfrida
Sonoita
Elgin
Charleston
Huachuca City
Tubac
Carmen
Canelo
Lewis Springs
McNeal
Apache
CORONADO
CHIRICAHUA


METEOR CRATER
4800
Winslow
7000
Puerco R.
5080
Holbrook
6000
PETRIFIED FOREST
LAVA FIELDS
MOGOLLON RIM
GALLO MTS.
WHITE MTS.
11500
SIERRA ANCHA
Salt R.
NATANES PLATEAU
Globe
MOGOLLON MTS.
GILA MTS.
Gila R.
Florence
PINALENO MTS.
MT. GRAHAM
10720
GALIURO MTS.
PELONCILLO MTS.
Gila R.
BURRO MTS.
CATALINA MTS.
9185
Tucson
RINCON MTS.
DOS CABEZAS MTS.
Willcox Playa
4280
PYRAMID MTS.
Benson
TUCSON MTS.
SANTA RITA MTS.
9432
CHIRICAHUA MTS.
HATCHET MTS.
8406
HUACHUCA MTS.
MULE MTS.
Bisbee
Nogales
3865
Douglas
4100

ERA	PERIOD	EPOCH	AGE (mil yr)	DOMINANT LIFE FORMS	EVENTS IN ARIZONA
CENOZOIC Age of Mammals	Quaternary *q*	Holocene	.01		Present erosion cycle gouges Pleistocene and Tertiary deposits. Basalt volcanism continues near San Francisco Peaks and at a few other sites.
		Pleistocene	2		Regional uplift accelerates erosion; cyclic erosion creates terraces. Basalt volcanism occurs in several areas; San Francisco Peaks grow, collapse, and are glaciated. Colorado River flows through to Gulf of California. Pluvial lakes occupy some valleys.
	Tertiary *t*	Pliocene	5		Colorado River turns west, initiates canyon cutting on Colorado Plateau. Little Colorado reverses as recurrent movements lift plateaus. In south, basins fill with stream and lake deposits.
		Miocene			Basin and Range Orogeny 15 to 8 million years ago creates fault-block ranges with NW-SE grain. Basalt volcanism widespread.
			24		Mid-Tertiary orogeny 30-20 million years ago pushes up mountains with NE-SW grain. Metamorphic core complexes form. Colorado Plateau rises; Colorado River flows south, east of Kaibab Arch. Downdropped Verde Valley intercepts northward drainage. Explosive volcanism common, with calderas in Chiricahua and Superstition Mountains.
		Oligocene	38		Tension faulting in south is accompanied by volcanism and intrusion of dikes, stocks, laccoliths. Intermountain valleys fill with debris from mountains. Verde Valley begins to form.
		Eocene	55		Laramide Orogeny ends 50 million years ago, leaving undrained intermountain valleys, some with lakes. No volcanism or intrusions mark "Eocene magma gap." Northbound streams deposit rim gravels.
		Paleocene	63		In south, Laramide Orogeny creates mountains with NE-SW trend: overthrusting may have occurred. Explosive volcanism occurs. Abundant small intrusions appear, some containing copper, silver, gold. In north, plateaus begin to form as large blocks are lifted or dropped.
MESOZOIC Age of Reptiles	Cretaceous K		138		Seas invade briefly from west and south; volcanism widespread. Laramide Orogeny begins 75 million years ago as west-drifting continent collides with outlying plates.
	Jurassic J		205		Deserts widespread; thick sand dune deposits in north. Explosive volcanism in south and west is followed by erosion.
	Triassic ℞		240		Extensive coastal plain, delta, and dune deposits spread north from mountains in central and southern Arizona. Faulting, small intrusions, explosive volcanism occur in south.
PALEOZOIC Age of Fishes	Permian P		290		Dunes form across northern Arizona, then a western sea invades briefly. Alternating marine and non-marine deposition in south and west.
	Pennsylvanian ℙ		330		Marine limestones deposited in south and south-central Arizona; floodplain and desert prevail in north.
	Mississippian M		365		Widespread deposition of fossil-bearing marine limestone is followed by emergence and development of karst topography with sinks and caves.
	Devonian D		410		Marine deposits form, then are removed from many areas by erosion.
	Silurian S		435		No record.
	Ordovician O		500		Brief marine invasion, then no record.
	Cambrian ∈				A western sea advances across denuded continent, depositing conglomerate and sandstone, then shale and limestone.
			570		Great Unconformity — long erosion.
PRE-CAMBRIAN *p∈*	Younger		1700		Several episodes of mountain-building and intrusions of sills and dikes are followed by marine and near-shore sedimentation, faulting, and uplift.
	Older				Sedimentary and volcanic rocks accumulate, then are compressed and altered into NE-SW-trending ranges extending beyond Arizona. 1.7 billion years ago granite batholiths intrude these older metamorphic rocks.

Minerals

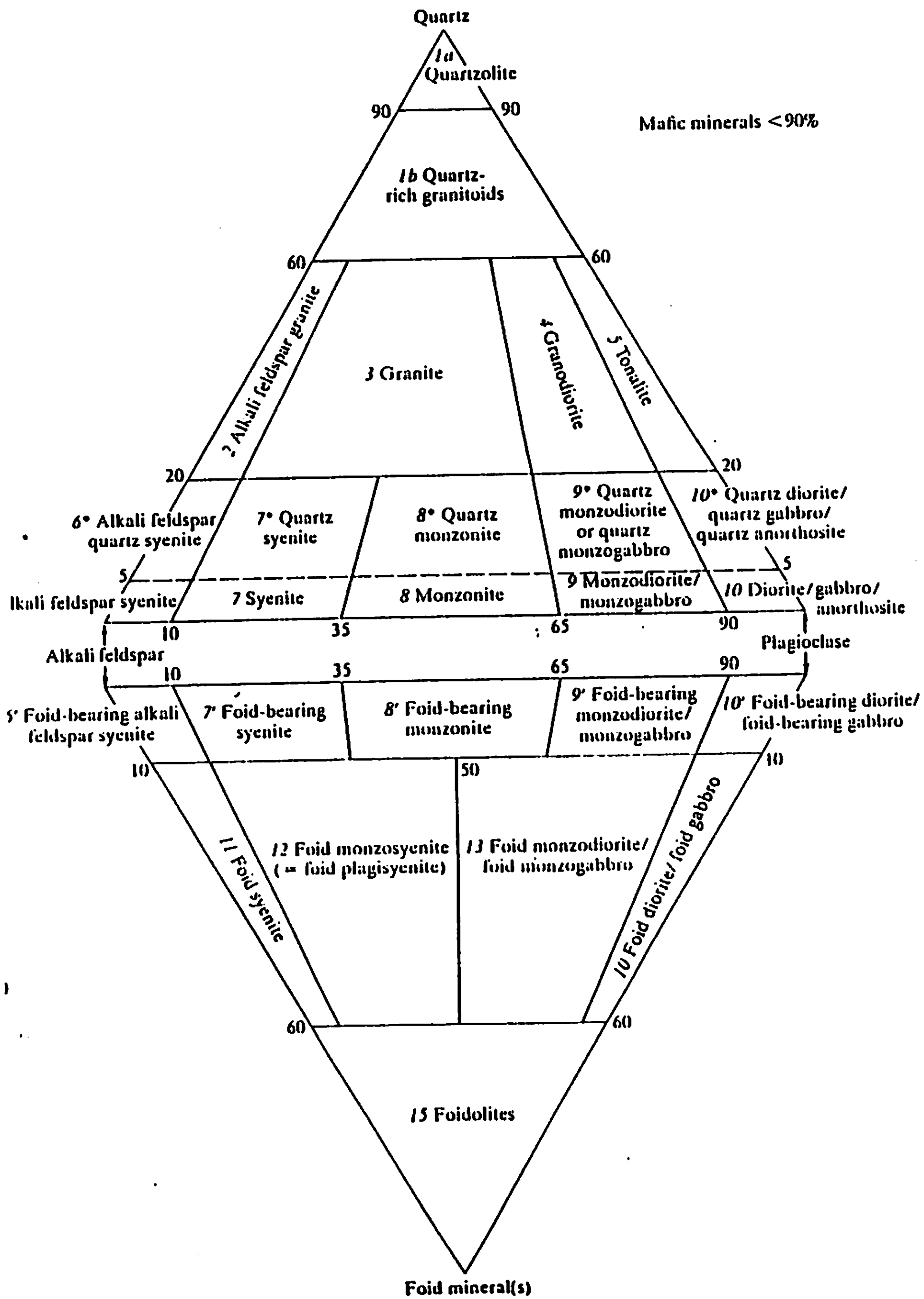
TABLE 1-3. Some Common Minerals and Their Physical Properties

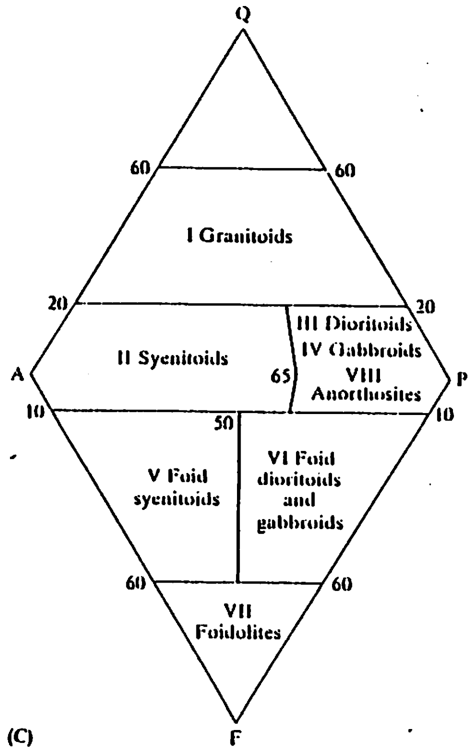
Mineral	*Chemical Composition*	*Common Colors*	*Luster*	*Hardness*	*Cleavage*
Quartz	SiO_2	Clear colorless, milky white, pink, gray, etc.	Glassy	7	None, concoidal fracture
Plagioclase	$NaAlSi_3O_8$ $CaAl_2Si_2O_8$	White, gray, colorless	Glassy to Pearly	6	Two directions, intersect at about 90°
Orthoclase (K-feldspar)	$KAlSi_3O_8$	Pink, white, gray, colorless	Glassy	6	Two directions, about 90°
Muscovite (white mica)	$KAl_3Si_3O_{10}(OH)_2$	Clear to silvery green, or yellow	Silky or Pearly	2–2.5	One direction, cleaves to thin sheets
Biotite (black mica)	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	Dark brown to black	Silky or Pearly	2.5–3	One direction, cleaves to thin sheets
Hornblende (Amphibole Group)	$Ca_2Na(Mg,Fe)_4(Al,Fe)(Al,Si)_8O_{22}(OH)_2$	Dark green to black	Glassy	5–6	Two directions, intersect at 56° and 124°
Augite (Pyroxene Group)	$Ca(Mg,Fe,Al)(Si,Al)_2O_6$	Dark green to black	Glassy	5–6	Two directions, intersect at 90°
Olivine	$(Mg,Fe)_2SiO_4$	Green to brown	Glassy	6.5–7	None, conchoidal fracture
Calcite	$CaCO_3$	Colorless to white	Glassy to Earthy	3	Three directions, intersecting at 75° and 105°
Pyrite	FeS_2	Pale brass-yellow	Metallic	6–6.5	none
Chalcopyrite	$CaFeS_2$	Brass yellow	Metallic	3.5–4	none

TABLE 1-4. Moh's Hardness Scale.

10	Diamond	↑
9	Corundum	
8	Topaz	
7	Quartz	
6	Orthoclase feldspar	increasing hardness
5	Apatite	
4	Fluorite	
3	Calcite	
2	Gypsum	
1	Talc	

Intrusive Rocks





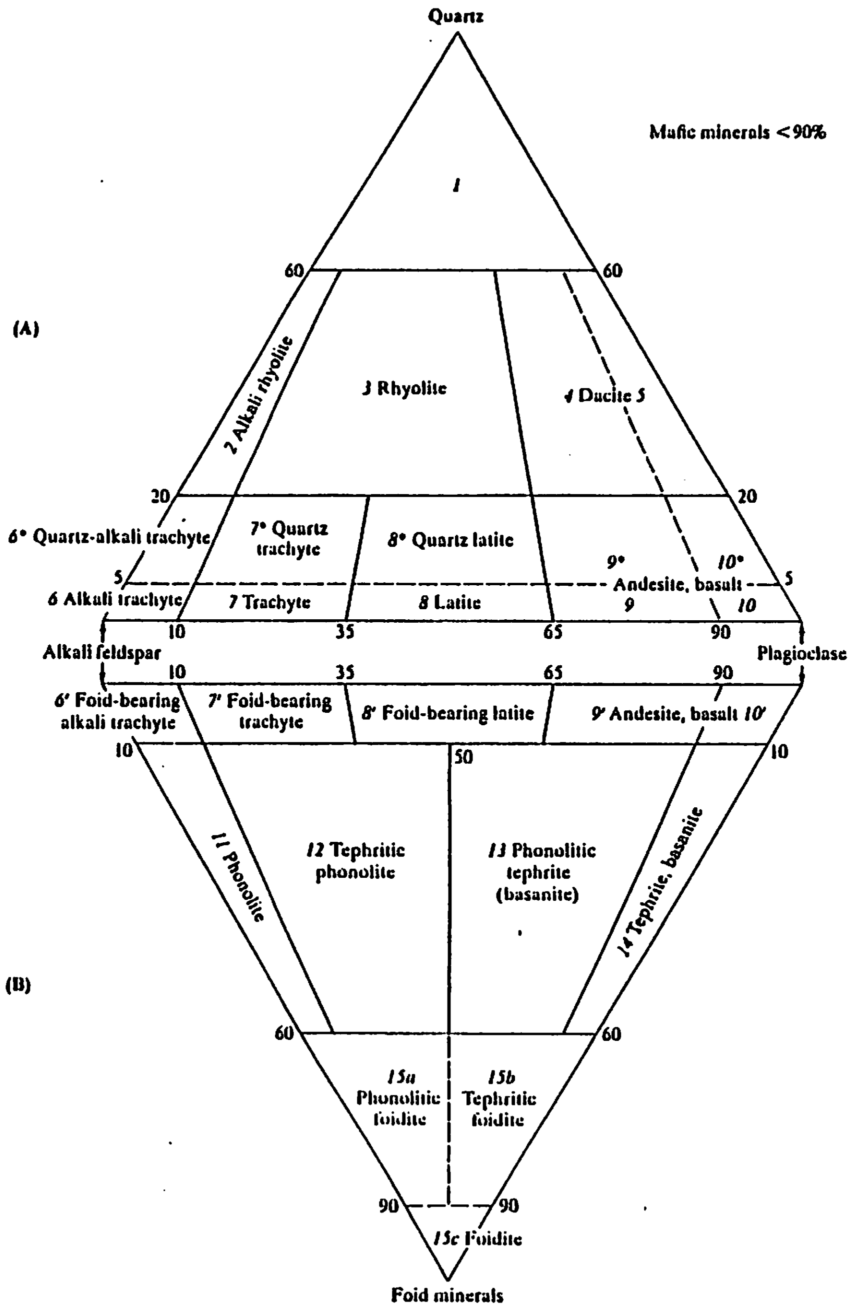
(C)

Figure 4–1
(A, B) The classification of plutonic rocks. In order to be included in these triangles, the igneous rock must be phaneritic. The rock must contain at least 10% plagioclase, alkali feldspar, and either quartz (triangle A) or feldspathoid (triangle B). The relative amounts of these minerals are recalculated to 100% and plotted within the appropriate triangle by the technique shown in Figure 4–2. Appropriate modifying terms are based upon mafic mineral composition or distinctive texture. (C) Generalized group names (for field use) when mineral percentages cannot be determined with precision. In fields II, III, and IV the qualifier "foid-bearing" should be used when feldspathoids are present. [From A. L. Streckeisen, 1976, *Earth Sci. Rev., 12,* Fig. 1a.]

(see Figure 4–1B). A rock cannot appear on both triangles, because quartz and feldspathoid are chemically incompatible; when mixed they will react to form a compound (feldspar) of intermediate silica content.

The volcanic igneous rocks are named on the basis of a similar triangular arrangement (see Figure 4–3). Distinction between basalt and andesite is made mainly on the basis of silica content (a rock with more than 52% SiO_2 is andesite, and a rock with less than 52% SiO_2 is basalt, as shown in part D), or less accurately on plagioclase composition (a rock with a plagioclase composition more sodic than An_{50} is andesite).

Extrusive Rocks



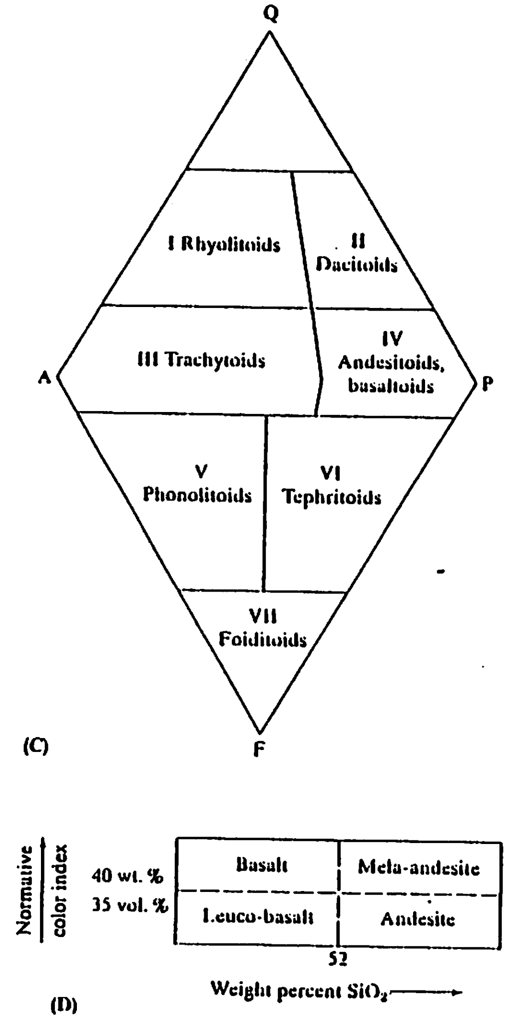


Figure 4–3
(A, B) The classification of volcanic igneous rocks. In order to be included within the triangles an igneous rock must be aphanitic. The rock must contain at least 10% plagioclase, alkali feldspar, and either quartz or feldspathoid (foid). The relative amounts of these three minerals are recalculated to 100% and plotted within the appropriate triangle, as shown in Figure 4–2. Appropriate modifying terms are used based upon mafic mineral composition or distinctive texture. In the case of those rocks whose matrix is too fine for determination, a tentative classification can be based upon minerals present in phenocrysts. (C) Generalized group names (for field use). (D) Distinction between basalt and andesite is based on color index (volume percentage of mafic minerals) and silica content. [From A. L. Streckeisen, 1979, *Geology*, 7, Figs. 1, 2; and A. Streckeisen, 1979, personal communication.]

confluence of an intermittently flowing tributary. The remainder of the trip is an easy, if occasionally brushy, 3-mile walk out to the Blue River. A wide variety of trees flourish along this stretch, including sycamore, walnut, maple, alligator juniper, ponderosa pine and Arizona cypress. Many of the trunks and branches are gaily festooned with wild grapevines, whose seedy but tasty fruits ripen in the fall and compensate the late-season traveler for the imminent loss of wildness at the trailhead.

After a mile or two Grant Creek may grow intermittent. All too soon we reach a barbed-wire fence and a sign indicating the primitive area boundary; the Blue River is just beyond. To reach Forest Road 281 we turn left and walk a short distance upstream to the point where the road swings into near contact with the river (19.1; 5440).

See Maps 23, 31 and 29

Trip 75 Sheep Crossing to Baldy Peak

13.8 miles round trip; 2180′ elevation gain

Moderate dayhike or backpack (2–3 hiking days)

Season June to September

Water available all season along first 3.2 miles of trail only

Features

Lush meadows, magnificent forests of spruce and fir, and a sparkling stream all lend their charms to this delightful alpine route. Views from the summit of 11,403-foot Baldy Peak are superlative, and the West Fork Little Colorado River offers good fishing for rainbow, brook and cutthroat trout.

Note: As of February 1985, the Baldy summit area has been closed to public entry. Hikers wishing to travel to the summit must obtain permission from the Fort Apache Reservation to travel beyond the reservation boundary at mile 6.3 (see address on page 182).

Description

From the trailhead at the Mount Baldy Wilderness boundary (0.0; 9220), our trail climbs gently beside the right bank of the West Fork Little Colorado. Fishermen will find this as good a

place as any to unpack their rods and reels, for the trail soon moves off to the right and maintains a rather inconvenient distance from the water. Along the fringes of this meadowed stretch the dominant tree is Colorado blue spruce, a lovely "frosted" conifer whose Arizona range is restricted to the White Mountains region and the area north of the main Colorado River near the Utah border. (A spruce may be distinguished from other evergreens by the square cross section of its needles, which makes them difficult to roll between one's thumb and forefinger. The Colorado blue may be told from the more common Engelmann spruce by squeezing a sprig of needles: if you say "Ouch!" you are holding a blue.)

The trail continues to climb gently away from the stream, but several small creeklets (water until early fall) provide refreshment along the mostly sunny, grassy canyonside. You may see some mule deer or elk grazing in the verdant greensward below, though you are more likely to see just a few head of cattle, members of the herds that are unfortunately still allowed to graze within the wilderness. The large boulders strewn about the canyon floor are glacial "erratics"—chunks of mountain debris that rode the ancient glaciers down from the Baldy summit area and were subsequently left stranded here when the icefields receded. Among the many wildflowers that flourish along this stretch are scarlet penstemon, meadow cinquefoil, leafybract aster and aspen fleabane.

About 2.5 miles from the trailhead, after gaining some fine views of Baldy Peak's densely forested flanks, we curve to the right and begin a wide, 180-degree circuit of a lush, inviting meadow. Immediately following the last glaciation of this area, this meadow was probably a small pond, its waters dammed up behind a "moraine," or wall of boulders which accumulated during a temporary halt in the glacier's retreat. (What is left of this moraine is now visible as the low, forested ridge adjoining the southeast edge of the meadow.) Over the millennia the pond filled with streamborne silt, becoming the meadow it is today; several centuries hence this natural succession may well culminate with the grasses being wholly replaced by the trees which are already invading the fringes of the meadow.

Soon the trail crosses a tributary of the West Fork (3.2; 9820), along whose banks camping is excellent. The forest cover here is less homogeneous than below; mixed in with the spruce you will find corkbark fir (an aptly named local variant of subalpine fir) and an occasional southwestern white pine. Here and there your eye may be caught by a showy yellow columbine blossoming in some moist, shady nook.

Beyond the meadow our route rounds a hillside, climbing steeply at times, until it once again parallels the West Fork Little Colorado southwestward. The canyon walls steepen as we enter a stand of Engelmann spruce, and the trail is soon forced to make a few switchbacks beneath some rocky bluffs. A short climb from here brings us to a notch atop a ridge (5.3; 10,860), where we are presented with a pleasant vista toward White Mountain Reservoir and the rolling country to the north. From this point on, the trail stays on top of or just below the crest of the ridge leading to the Baldy summit area, and it is not advisable to proceed farther if a thunderstorm seems imminent.

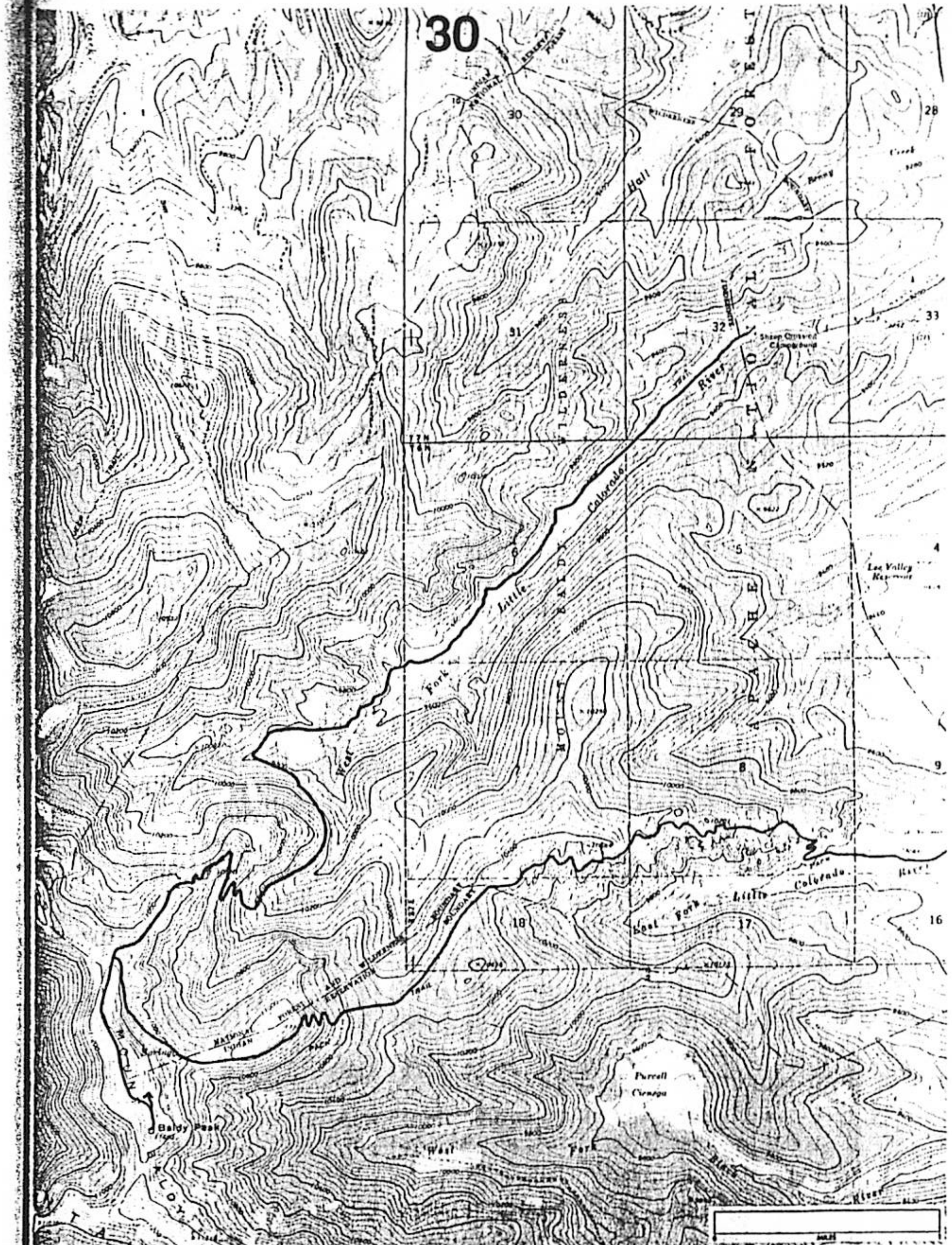
Continuing our moderate ascent, we soon meet the signed East Fork Little Colorado River Trail coming up from the east (6.1; 11,180). A few poor, exposed campsites can be found here, but the nearest water is 0.4 mile away, at a tiny spring down on the East Fork Trail. From the junction we continue south across a gentle rise, then drop slightly into a shallow saddle before finally scrambling onto the rocky summit of Baldy Peak (6.9; 11,403). (Just beneath the top a faint trail branches off to the left. This is the old East Fork Trail, which is no longer maintained and not recommended for travel.)

On the summit you will find a register to sign, and extensive views in every direction. A mile to the northwest is 11,036-foot Mount Warren, easily recognizable by the light green "hanging meadow" which contrasts so sharply with the dark forests on its southeast flank. Due west is 11,150-foot Paradise Butte, rising abruptly above the deep gash of the East Fork White River canyon. Beyond the Butte, ridge after forested ridge falls away toward the horizon; on a clear day one can see nearly halfway across the state in this direction.

After taking in the view, return the way you came, or via the East Fork Trail (4 mile car shuttle required; reverse the steps of Trip 76.)

See Map 30

30



The El Capitan and Cross Hill Catastrophic Landslide

With your most catastrophic hosts

☞ Will Grundy and Mark Lemmon ☜

Vitally catastrophic statistics

Volume of rock:	4×10^7 m^3	Time of emplacement:	Pleistocene (?)
Max vertical drop:	1300 m	Max horizontal travel:	6800 m
Deposit thickness:	5 - 35 m	Width of deposits:	1500 m
Max exposed length:	3800 m		

Cross Hill

volume: ~ 20×10^6 m^3

area: > 6 km^2

thickness: 1 - 50 m

other data ???

Catastrophic references:

Howard, K.A. (1973) Avalanche Mode of Motion: Implications From Lunar Examples. *Science* 180, 1052-1055.

Hsü, K.J. (1975) Catastrophic Debris Streams (Sturzstroms) Generated by Rockfalls. *G.S.A. Bull.* 86, 129-140.

Krieger, M.H. (1977) Large Landslides, Composed of Megabreccia, Interbedded in Miocene Basin Deposits, Southeastern Arizona. Geological Survey Professional Paper 1008, Washington D.C.

★Melosh, Sir H.J. (1986) The Physics of Very Large Landslides. *Acta Mechanica* 64, 89-99.

Shreve, R.L. (1968) Leakage and Fluidization in Air-Layer Lubricated Avalanches. *G.S.A. Bull.* 79, 653-658.

Yarnold, J.C., and J.P. Lombard (1989) A Facies Model for Large Rock-Avalanche Deposits Formed in Dry Climates. in Conglomerates in Basin Analysis: A Symposium Dedicated to A.O. Woodford: Pacific Section S.E.P.M. 62, 9-31.

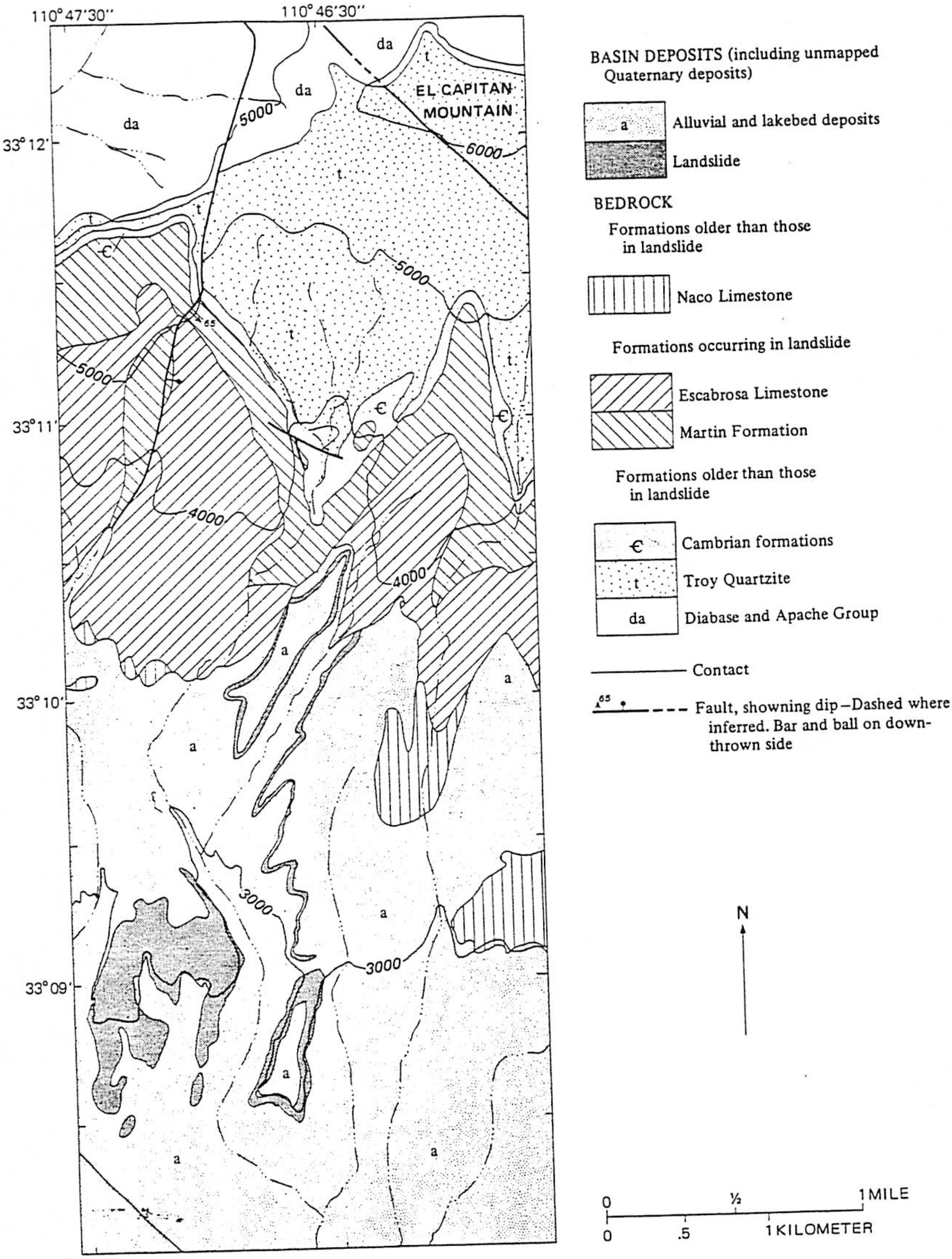


FIGURE 27.—El Capitan landslide and its source area on El Capitan Mountain. Reduced from geologic map of El Capitan Mountain quadrangle (Cornwall and Krieger, 1977).

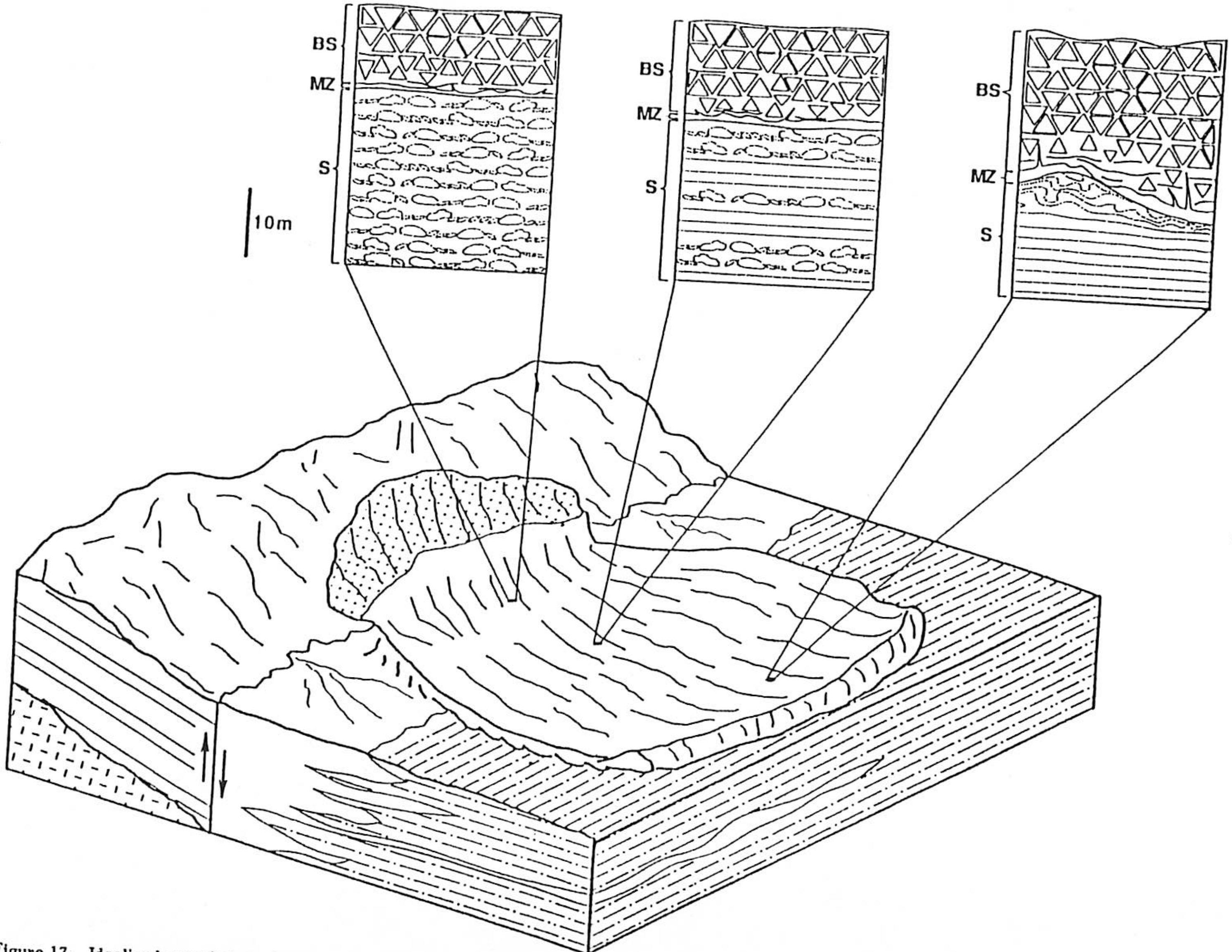
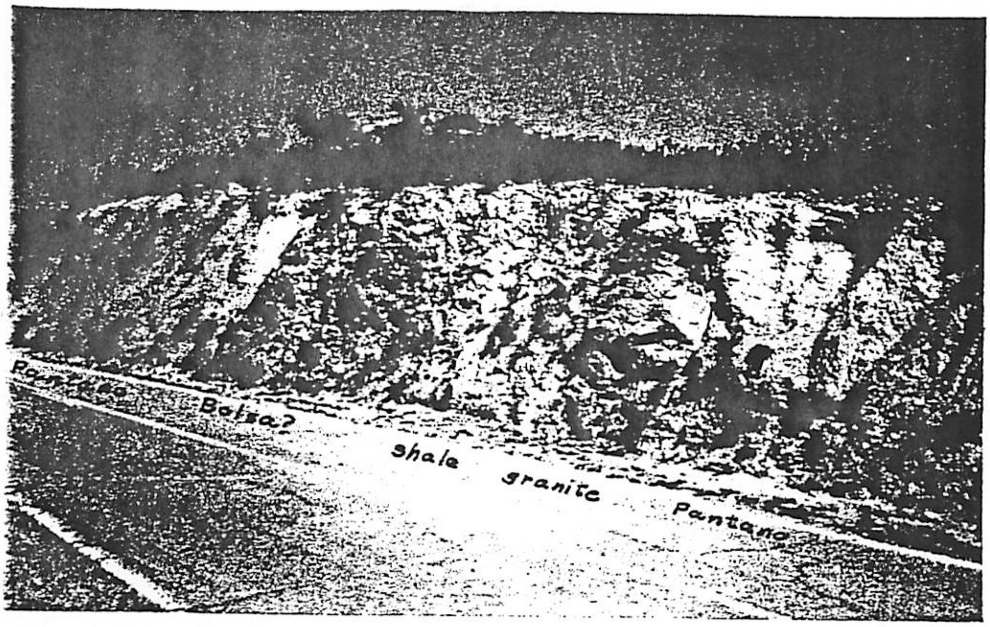


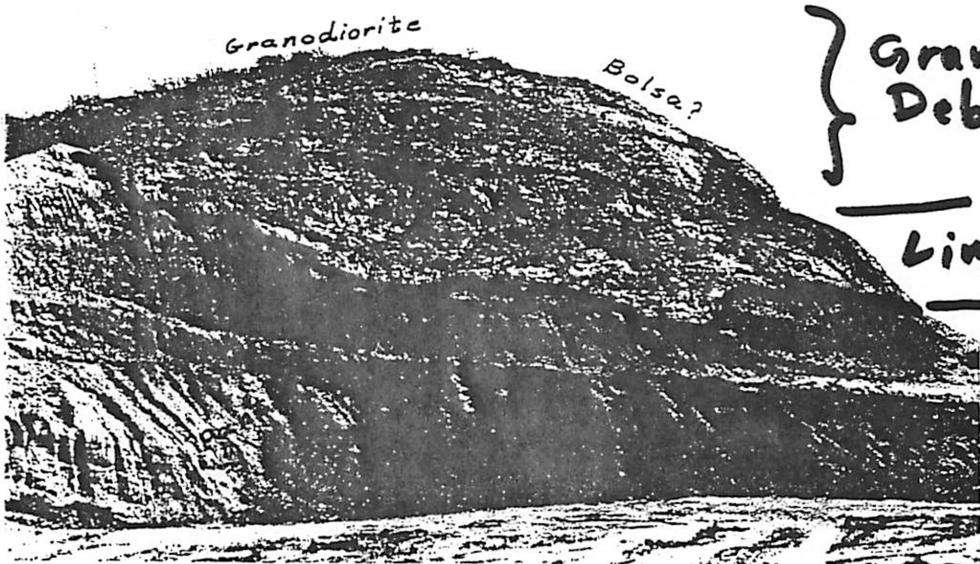
Figure 17. Idealized morphology (not to scale) of large dry-climate rock-avalanche deposit showing internal features and associated substrate lithofacies in proximal, medial, and distal portions. Abbreviations are the same as in Figure 15. Approximate vertical scale is indicated for zonal stratigraphic columns.

A



Cross Hill Quarry- Approach

B



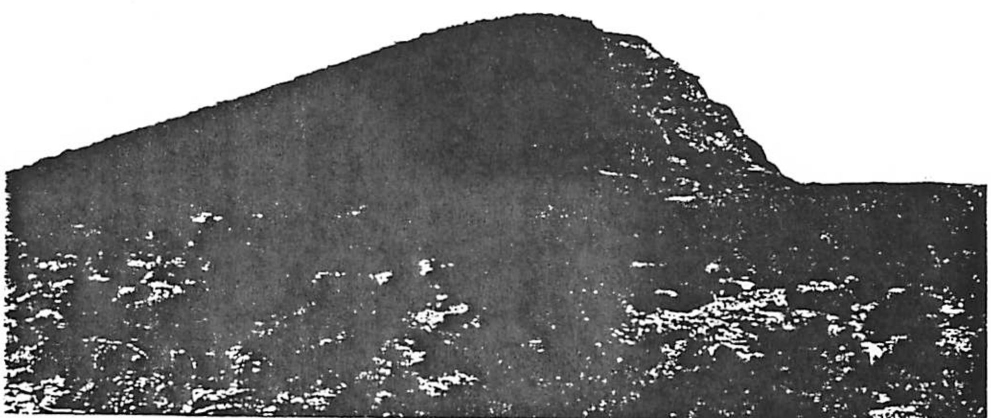
Granodiorite Debris

Limestow Debris

Pantano fm. clay

Front (view to N)

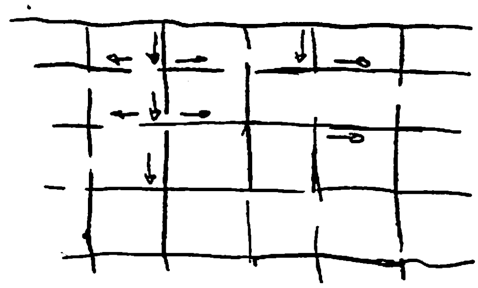
C



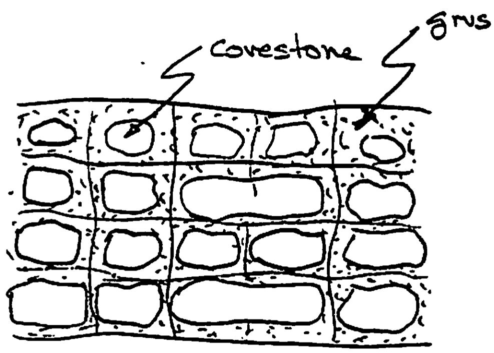
Side (view to E)

Spheroidal Weathering - Texas Canyon

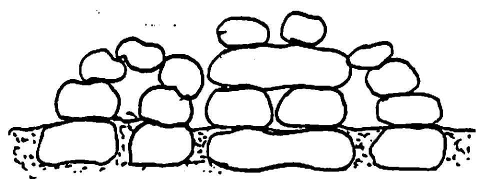
① Water infiltrates competent orthogonally jointed rock.



② Subsurface chemical weathering occurs. Shape and size of intact pieces are determined by joints



③ Erosion removes debris exposing boulders. Weathering and erosion continues.



Features may be called: tors, boulder fields, stacks, rock towers, castle koppies,

Process is similar to exfoliation.

Balanced boulders can be used as tools in paleoseismology.

References:

Easterbrook, Don J., Surface Properties and Landforms

Gerrard, A.J., Rocks and Landforms, 1988.

Stein, R. "Being Struck by Balance", Nature, 29 Feb 96.

Twidale, C.R., Structural Landforms, 1971

Raising Metamorphic Core Complexes

Big picture: Overthickened crust extends due to gravitational collapse. Low angle detachment faults expose buried metamorphic rocks. [An overly simplistic story re-told by Andy Freed]

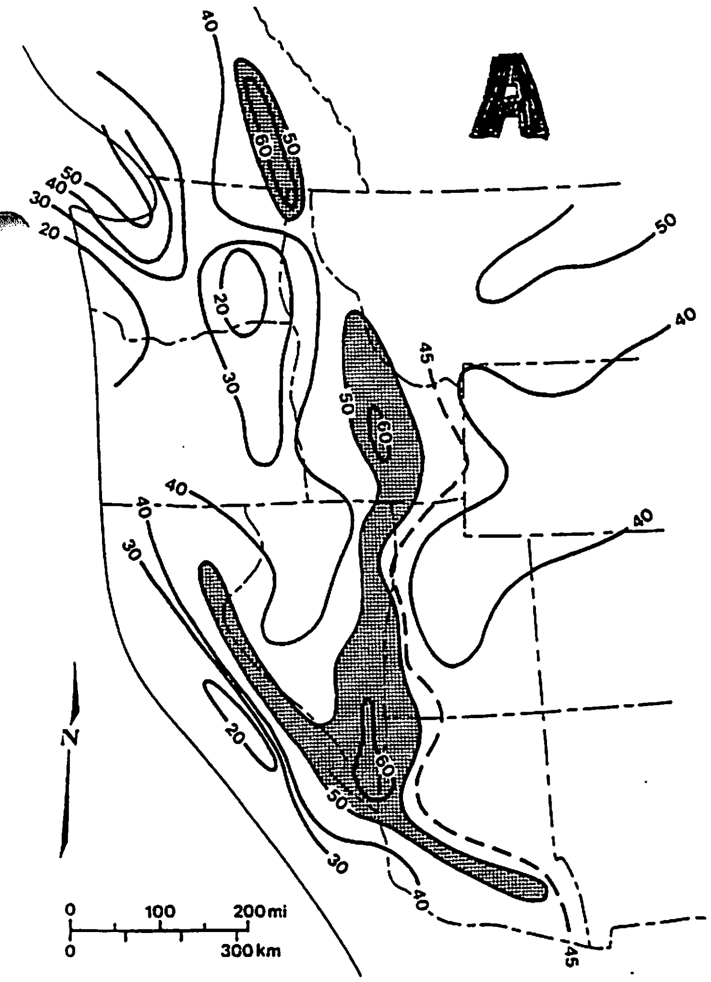


Figure 4. Post-Laramide palinspastic and paleoisopach reconstruction and resulting crustal welt. Crustal thickness contours (km) and palinspastic base derived from restoration of early and mid-Tertiary extension and crustal thinning. Welt of overthickened crust (strippled area), which was the consequence of Sevier-Columbia-Laramide telescoping, runs down axis of Cordillera and coincides with locus of later core-complex extension.

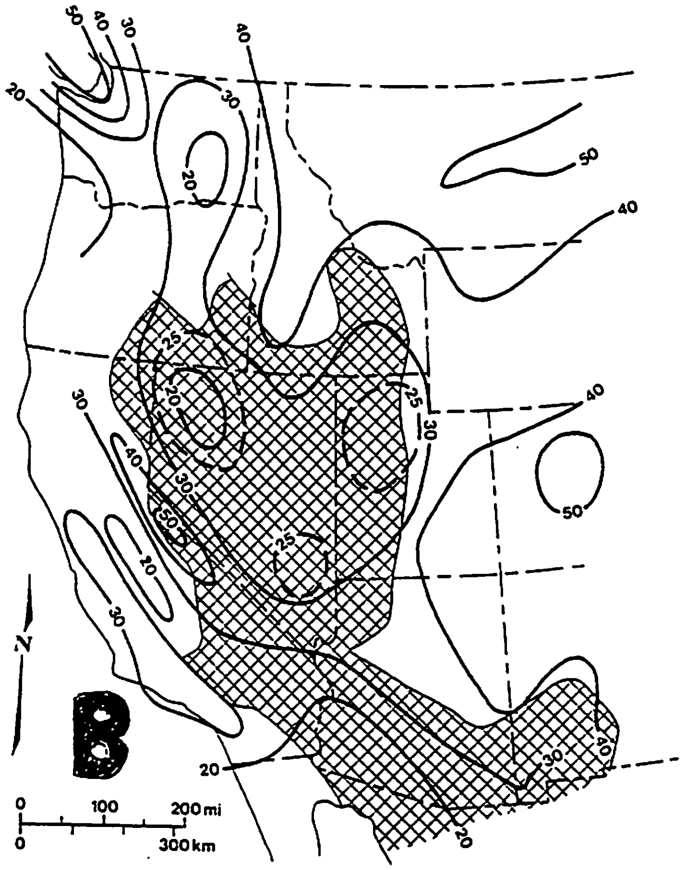


Figure 2. Present crustal isopachs and Basin and Range extensional province. Contours show present crustal thickness (km) on present-day base map. Cross-hatch pattern indicates area of Basin and Range extension.

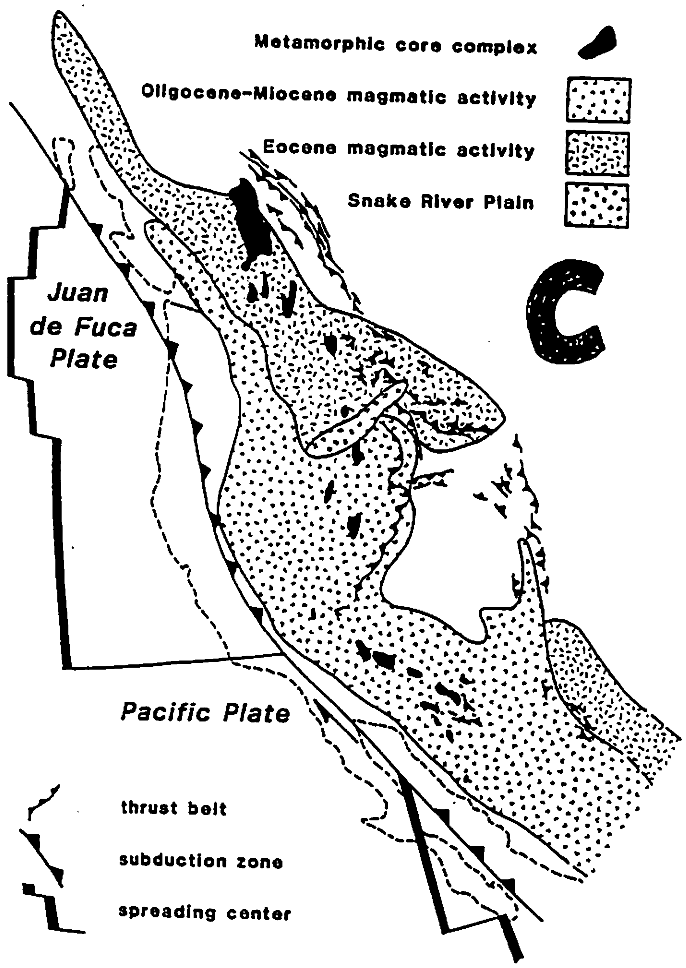


Figure 1. Major regional tectonic features of early and middle Tertiary post-Laramide, pre-Basin and Range time. From Coney (1978, 1980).

Raising Metamorphs (cont)

Little Picture: Metamorphic rocks exposed by detachment faulting, then raised and upwarped by isostatic forces.

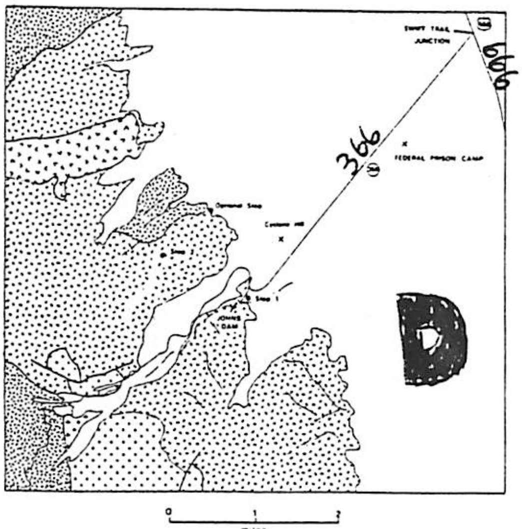


Figure 2. Generalized geologic map of the northeastern Pinaleno Mountains showing the field-trip route, stops 1 and 2, and the optional stop. The map units are Gneiss of the Pinaleno Mountains (heavy, dense chicken-track pattern); Gneiss of Johns Dam (light, less dense chicken-track pattern); Granite of Veach Ridge (+ pattern); Granite of Slick Rock (v pattern); and metarhyolite dikes (solid line with cross bars). All units are Proterozoic in age.

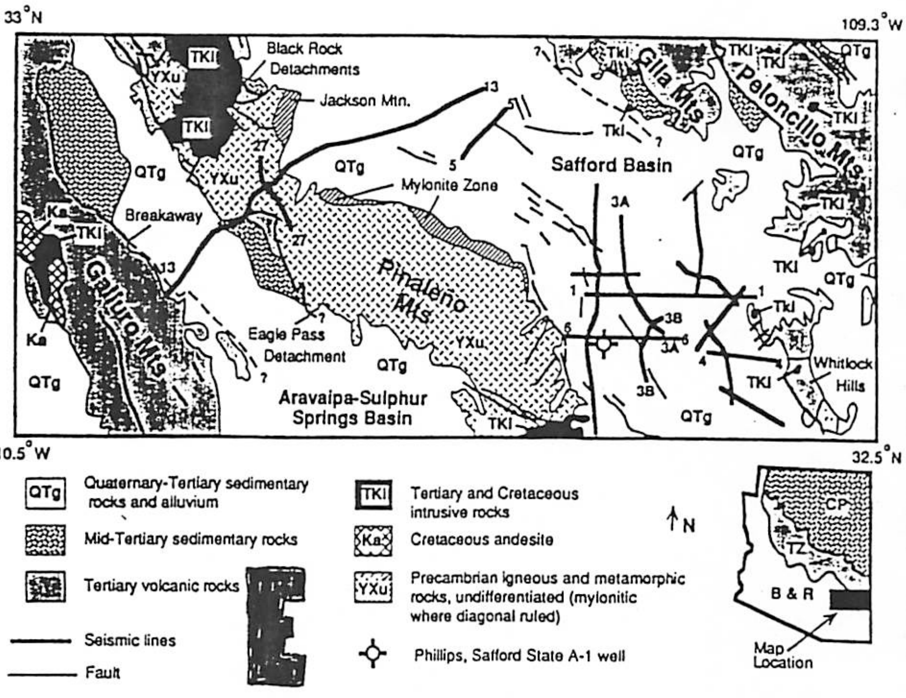


Figure 1. Simplified geologic map of Pinaleño Mountains and surrounding area (modified from Naruk, 1987). CP is Colorado Plateau; TZ is transition zone; B & R is Basin and Range.

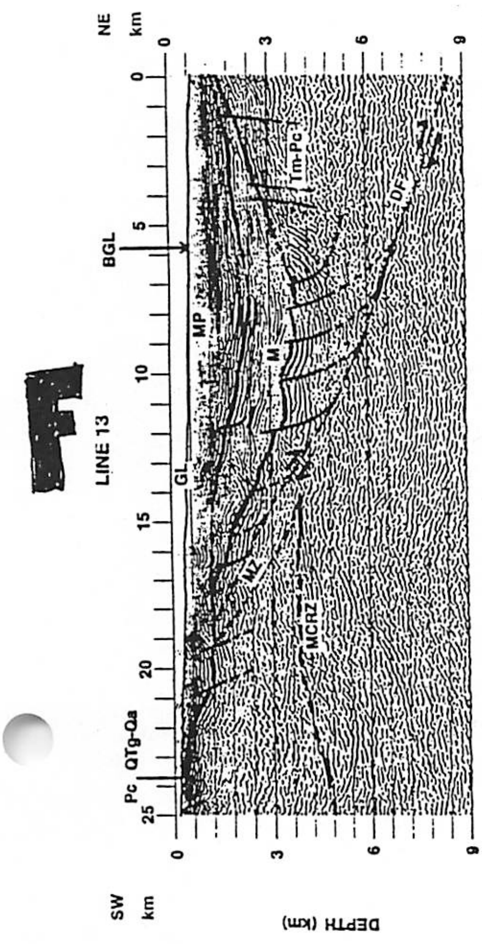


Figure 4. Upper 9 km of interpreted finite-difference-migrated depth section of northeastern end of line 13 showing Safford basin and underlying mid-Tertiary units, detachment fault, mylonite zone, and mid-crustal reflective zone. This section extends from northeastern end of line to location 1 km southwest of Precambrian basin-fill contact. No vertical exaggeration. Abbreviations are same as in Figures 2 and 3, plus M—Miocene basin fill; DF—detachment fault (originally same as Eagle Pass detachment fault?); MZ—mylonite zone exposed on northeastern flank of Pinaleño Mountains; MCRZ—top of mid-crustal reflective zone. Arrows indicate relative movement across detachment fault. Arrows not shown on other normal faults.

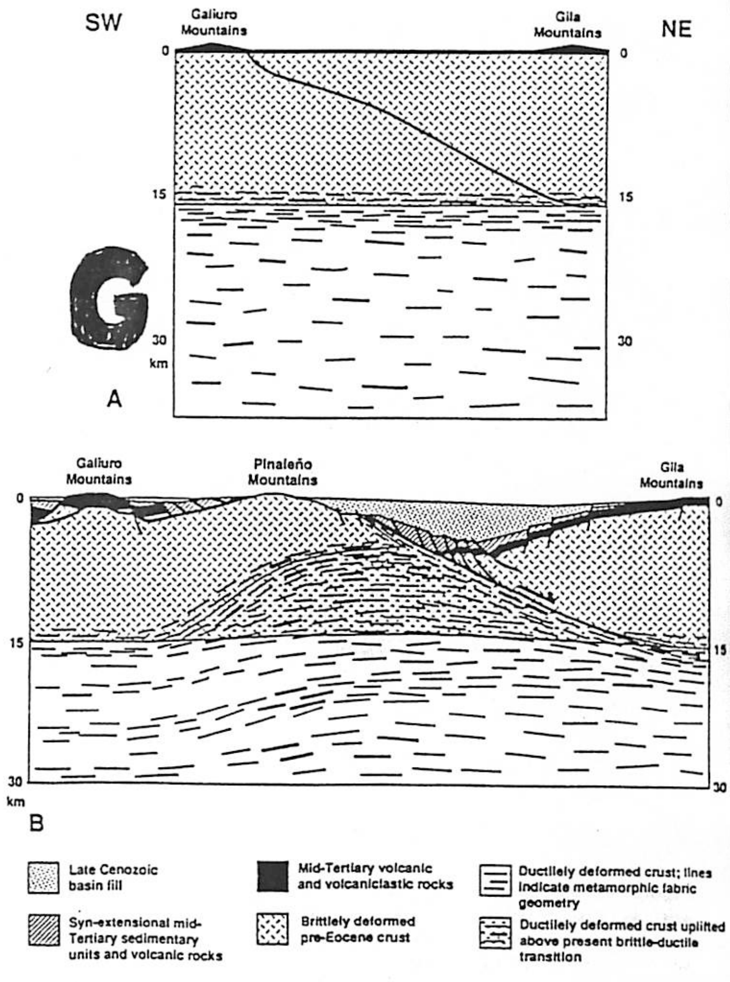


Figure 5. Schematic cross sections from Galiuro Mountains to Gila Mountains approximately along line 13, prior to movement along Eagle Pass detachment-fault system (A) and today (B). Approximately no vertical exaggeration. Incipient Eagle Pass detachment-fault system extends from surface near northeast flank of Galiuro Mountains and flattens within brittle-ductile transition below Gila Mountains. Mid-Tertiary extension progressed and uplift of core complex occurred as upper crust was tectonically denuded.

Copper

Mining Porphyry Deposits
or
Red Giants to Arizona to Your Pocket

Eric Wegryn

Copper is a nice, shiny, copper-colored metal. It is nice because it is very electrically and thermally conductive, ductile and malleable, and resistant to corrosion. Because of these properties, it is one of the more useful elements, as opposed to, say, yttrium, or rhenium, or those *boring* non-descript rare earth elements. Copper is ideal for use in electrical devices, and indeed, at present over 75% of all copper is used in electronics and electrical applications.

All the copper in the world was created in the advanced nuclear burning stages of red giant stars billions of years ago. How some of it came to be part of our planet is beyond the scope of this work. How much of it ended up in Arizona would be slightly more relevant. How it comes to be dug out of the ground, separated from the surrounding rock, purified, and fashioned into nice things such as pennies and electrical wiring is bang on, so it is this last story on which we shall focus. As one chronicler of the history of copper mining said, "Whatever Power is responsible for the Universe made ore deposits; but mines are made by the genius of men."[1]

Arizona's extensive deposits of copper-bearing rock have made it the largest copper producing state in the U.S., with more production than all the other states combined. The oldest and most productive mine in the state is located at Morenci, near the New Mexico border. Copper was first mined at Morenci in 1872 (see chronology below), from the very richest "bonanza" sources, veins or sheets near the surface. As these high-yield deposits were quickly used up, more intensive techniques had to be employed to mine the copper. The bulk of the deposits are low-grade porphyry deposits, which contain much smaller amounts (less than 2% by mass) of copper, in crystals which are distributed fairly evenly throughout the deposit, and in thin coats along fracture planes.

As early as 1893 a struggling Arizona Copper Co. had to consider mining the low-grade porphyry copper at Morenci. The term porphyry refers to igneous rock containing conspicuous crystals (phenocrysts) in a fine-grained groundmass. It is formed when a molten magma intrudes or invades existing rock, and as it solidifies, develops the porphyritic structure of relatively prominent (0.1 mm sized) crystals in a much finer-grained groundmass. This genesis is followed by a period of secondary (or supergene) enrichment, as acidic solutions leach copper and repreciptate it lower down. The result is a porphyry deposit enriched with chalcocite under a leached capping layer.

In the case of Morenci, a predominately quartz monzonite magma intruded on the regional limestone and shale to create a porphyry deposit about 1400 x 900 m and averaging 250 m thick, with chalcocite (Cu_2S) grains, and pyrite (FeS_2), chalcopyrite ($CuFeS_2$), and sphalerite (FeS) veins, beneath a capping layer about 80 m thick.[2,3] Although it is a geological term, the word "Porphyry" is also commonly used to refer to the major copper mines, even if the ore is not porphyry, and Morenci is considered one of the original "Porphyries".

The extent of a deposit which can be profitably mined is determined by boring for numerous samples, and using the assay results to delineate the region to be excavated. Obviously though, the definition of what is profitable varies from mine to mine, and changes with increasing technology and with the supply and demand for copper. As the percent yield of the remaining ores decreases, it becomes necessary to make use of lower grade ore through improvements in technology and efficiency.[2] Even the richest porphyry ores remaining today contain less than 1% copper. For this reason, economies of scale usually dictate the necessity for open pit mining, the removal of enormous quantities of overlying "waste" rock to reach the porphyry ore and remove it in bulk quantities. As a result, Morenci and other open pit copper mines are among the largest man-made things on Earth.

Open pit mining commenced at Morenci in 1937, and large scale exploitation of the orebody began in 1942 with the construction of a new concentration facility. To profitably extract the copper from the deposit, it is necessary to remove great amounts (up to 2.5 parts) of waste rock to get to good ore. Great diesel trucks, arguably one of the most significant developments in open pit mining, are used to haul the ore out of the huge chasm, up to 190 tons per load. The mine grows deeper and wider, a gaping man-made crater marked by tiers of horizontal benches 50 feet (15.2 m) high. As one observer remarked, "Perhaps the principle impression is one of hugeness; of wonder in the capacity of mere man to make this tremendous scar on the bosom of the eternal Earth . . ."[1]

Once the ore is extracted, it must be processed to remove the small quantity of copper it contains. Two basic methods are available. Most (~ 85%) of the copper in porphyry ores exists in sulfides (chiefly chalcocite and chalcopyrite). The extraction process begins with concentration (milling). The ore is crushed and ground up to free the copper-bearing crystals from the rock. The next step is flotation, in which the powdered ore is mixed with water so the copper grains can be preferentially coated with chemical reagents, brought to the surface by air bubbles, and separated off. Up to 95% of the copper can be separated into less than 3% of the original mass of the ore; the remaining copper ends up in the tailings.

The concentrate is then sent to a smelter, where it is roasted to drive off some of the sulfur and volatile impurities, then melted in large reverberatory furnaces. The resulting mixture of iron sulfide (FeS) and copper sulfide (Cu_2S), called matte, is transferred to a Bessemer converter where the iron is slagged and the sulfur burned off, leaving 99.5% pure "blister" copper. This is remelted and cast into large anodes, which are sent to an electrolytic refinery, where they are dissolved in solution and reprecipitated at a cathode, yielding 99.9% pure copper.

For ores rich in copper oxides (*e.g.* as a result of weathering), an alternate technique is leaching, percolating through sulfuric acid to dissolve the copper, after which the copper sulfate solution is directly electroplated onto cathodes. This is known as the solvent extraction / electrowinning (SX/EW) process. A new facility for this process was constructed at Morenci in 1987 to continue supplying high quality copper for decades to come.[4]

The world's supply of new copper comes from a surprisingly few copper mines, most of them open-pit porphyry mines. Undoubtedly there exist deposits still hidden, but the overall supply is obviously limited. Fortunately, copper is one of the most easily recyclable metals, and "used" copper can now supply over half of our copper needs. Still, the mining of copper is an impressive feat, which has undergone great technological advancements. Every effort should be made to pull all of this metal out of the earth. After all, "If it had not been for the application of brains and capital to the development of this copper, these properties would be so much worthless rock in mountains of scenic value only."[3]

A brief chronology of the Morenci mines:

1872 Federal Mining Law; First claims at Morenci; town of Clifton founded
1874 Detroit Copper Mining Company organized
1875 First smelter (led to first railroad in Arizona)
1881 Phelps, Dodge & Co. invests in new smelter for Detroit Copper
1884 Arizona Copper Company organized
1886 Bonanza ores exhausted; First concentrator in Arizona built
1892 James Colquhoun appointed General Manager of a struggling Arizona Copper Co.; he institutes leaching of porphyry copper with sulfuric acid, leads to company's first profits
1897 Phelps, Dodge & Co. buys Detroit Copper Mining Co.
1922 Phelps, Dodge & Co. buys Arizona Copper Co. (with its Metcalf mine)
1932 All mining temporarily halted due to the Great Depression
1937 Phelps Dodge begins open-pit mining at Morenci
1942 New concentrator and smelter built between Morenci and Clifton; large-scale mining begins in earnest
1948 Molybdenum separator added
1974 New Metcalf concentrator built
1985 Phelps Dodge Inc. sells 15% of Morenci to Sumitomo Metal Mining, of Japan
1987 New SX/EW plant constructed
1989 Movable in-pit crushers and conveyors transport ore more efficiently

References:

[1] A.B. Parsons, *The Porphyry Coppers*, 1933

[2] A.B. Parsons, *The Porphyry Coppers in 1956*, 1956

[3] F.J. Tuck, *Stories of Arizona Copper Mines*, 1957

[4] R.R. Beard, *The Primary Copper Industry of Arizona*, 1985

The Ill-Considered and Hastily Constructed Apache History Handout

or Keeping Your Head While Losing Your Scalp

with your range-ridin' hornswagglin' rootin' tootin' guide, Andy Rivkin

Cast of Characters:

- Geronimo (1829–1909): Chiracahua Apache medicine man, led "final" Apache raids in 1880's
- Cochise (?–1874): Chiracahua Apache chief, led raids in 1860's and 1870's
- General George Crook (1829–1890): Commander, Department of Arizona. First to use Apache scouts in fight against Apache outlaws, compelled Cochise to surrender
- General Nelson Miles: Crook's successor as commander. Caught Geronimo in 1886, went on to capture Puerto Rico for the U.S. during the Spanish-American War.
- The Apache Kid (c. 1860–1890's? 1907? 1920's?): San Carlos Apache outlaw
- Charlie McComas (1877–?): Kidnapped settler's son turned Apache outlaw chief
- Indian Juan (?–1931): Brutal Apache outlaw in Sonora

Rough Timeline:

- c. 1000: First Apache ancestors may have reached Southwest.
- 1500 and later: Introduction of horse leads to Comanches and Utes speeding Apache migration south and west.
- 1600's: Apaches begin raiding Spanish missions.
- c. 1700: Some Apaches still living as far north and east as Kansas.
- 1821: Mexico becomes independent.
- 1846: Mexican War begins, Apache raids in Sonora kill over 100 Mexicans.
- 1848: Mexican War ends, Arizona north of Gila River ceded to U.S. from Mexico. Apache raids continue to trouble Sonora.
- 1853: Gadsden Purchase transfers rest of Arizona to U.S..

- 1858: Meeting at Apache Pass in Dragoons leads to peace between U.S. and Chiracahua Apache. Also, Mexican revenge attack kills Geronimo's family.
- 1861: U.S. Civil War begins, troops called east from New Mexico Territory (then comprising Arizona and New Mexico). Also, Cochise leads Apaches on warpath.
- 1865: U.S. Civil War ends, Indian wars begin again in earnest.
- 1871: In April, 150 Mexicans, Papagos and Anglos kill over 100 Apaches (mostly women and children) in Camp Grant Massacre. Gen. Crook takes command of the Department of Arizona. Cochise surrenders in September.
- 1872: Cochise escapes reservation in spring, surrenders again for good in summer.
- 1880's Unhappy (for any number of valid and invalid reasons) on the reservation, Apache raids become more and more common, led by Geronimo.
- 1884: Geronimo surrenders to San Carlos reservation.
- 1885: Geronimo leaves reservation with followers in May.
- 1886: Geronimo surrenders in Sonora in late March, but near border with U.S. bolts with a small band. Crook replaced by Gen. Miles, who gains final surrender in September.
- 1880's-1920's: Apache raids continue in U.S. with less and less frequency, "Bronco Apaches" hide out in Sierra Madres along Sonora-Chihuahua border. Mexican victims of Apache raids take stronger and stronger measures verging on genocide until finally raids cease.

The earliest known photo of Geronimo, taken by photographer A. Frank Randall at San Carlos reservation in 1884. This is the face that launched a hundred articles, stories, and novels.

General Nelson A. Miles

A f[illegible] scout for the U.S. Army, the Apache Kid robbed, raped and murder[illegible] way across the southwest. He was never captured and was said to have died of old age in an Apache camp in Sonora during the 20th century. (Courtesy Arizona Historical Society)

Glacial Deposits

Elizabeth P. Turtle

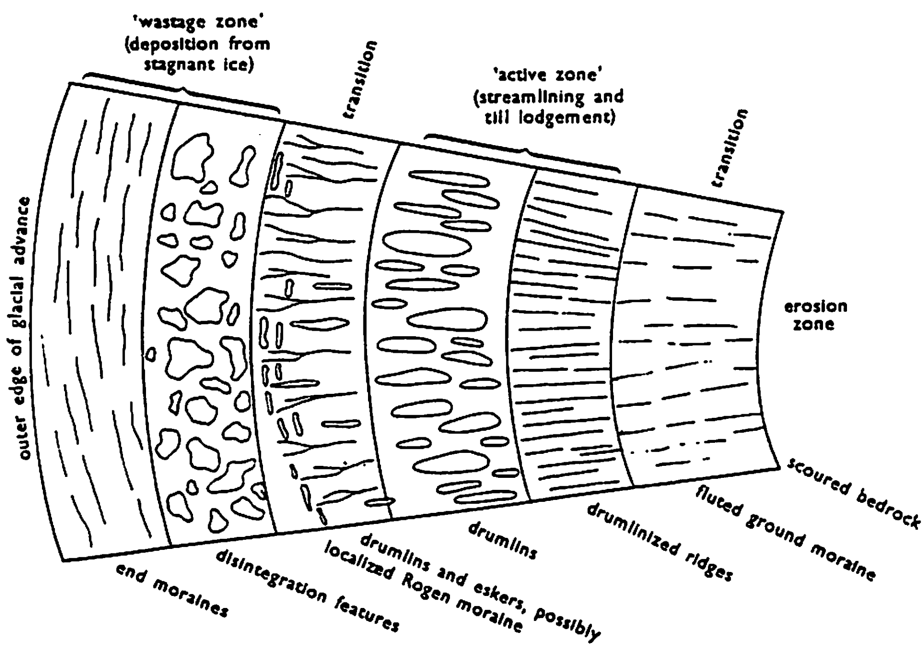
Terms

Drift -- all encompassing term for glacial sediment. Includes sediment deposited directly by glaciers and that deposited indirectly through rivers, lakes and oceans. There are two classifications of drift which grade into one another:

- **Till** -- unsorted rock particles deposited directly where they were released from the ice. The surfaces of larger rocks in till are faceted and have smoothed edges due to grinding and polishing within the ice. They often display striations. Small particles are usually rock flour which is fine sand of silt comprised of fresh, unweathered, jagged particles created by crushing of rocks by the glacier.
- **Stratified drift** -- particles deposited indirectly by glacial meltwater and thereby sorted.

Landforms

Glaciers generate a wide variety of landforms and there are almost as many classification schemes as there are glaciologists. The figure below (from Sugden and John) shows broad categories of depositional features and the conditions under which they form.



Goldthwait (1988) includes a five page table classifying different glacigenic landforms. The following table is a simplified version concentrating on depositional features relevant to the White Mountains and (possible) Mars:

Direct deposition [in contact with ice, composed primarily of till]

Subglacial

parallel to ice motion [active, warm-based ice]

Streamlined drift -- assemblage of oval hills shaped by erosion and/or deposition by ice. Includes drumlins, drumlinized ridges, fluted moraines, crags-and-tails.

transverse or unoriented

moraine ridges -- systematic sets of ridges ranging from straight to crescent-shaped usually formed under moving ice. Includes corrugated, Rogen, and thrust moraines.

ground moraine -- ranging from smooth to hummocky, thin to thick: cover moraine [patchy, thin veneer over bedrock], hummocky ground moraine [irregular area, rolling or rough], till plain [nearly flat, thick, often composed of multiple till layers]

Ice Margins [slow-moving ice]

parallel to ice motion

lateral moraine -- sharp ridges along sides of valley glaciers also includes perched or stranded moraines and medial moraines.

transverse or unoriented

marginal moraines -- perpendicular to ice motion, includes end/terminal/recessional moraines [created by dumping] and push moraines [created by thrusting]

miscellaneous moraines -- crevasse filling and moraine dump [stagnant, wasting ice]

Etc.

Erratics -- boulders carried by glaciers and deposited away from their source on bedrock of different composition.

Kettles -- Depression left in drift after melting of a partially or completely buried, isolated block of ice.

Indirect deposition [meltwater induced or fed, usually well-sorted]

Subglacial [in contact with warm-based, slow-moving ice]

<u>Eskers</u> -- sinuous, steep-walled, stratified ridges deposited by streams running through tunnels in the ice.

Ice margin [in contact with slow or stagnant ice but subaerial]

<u>Kame fields</u> -- patches of irregular hummocks and short ridges from material that collected in openings in stagnant ice.

<u>Kame terrace</u> -- stratified drift deposited between wasting glacier and valley walls.

Glaciofluvial features -- fluvial deposition (often alternating sand and gravel beds) usually downstream of but sometimes on or even under thin ice with shallow, braided channels. Includes <u>outwash fans</u>, <u>valley trains</u>, and <u>outwash terraces</u>.

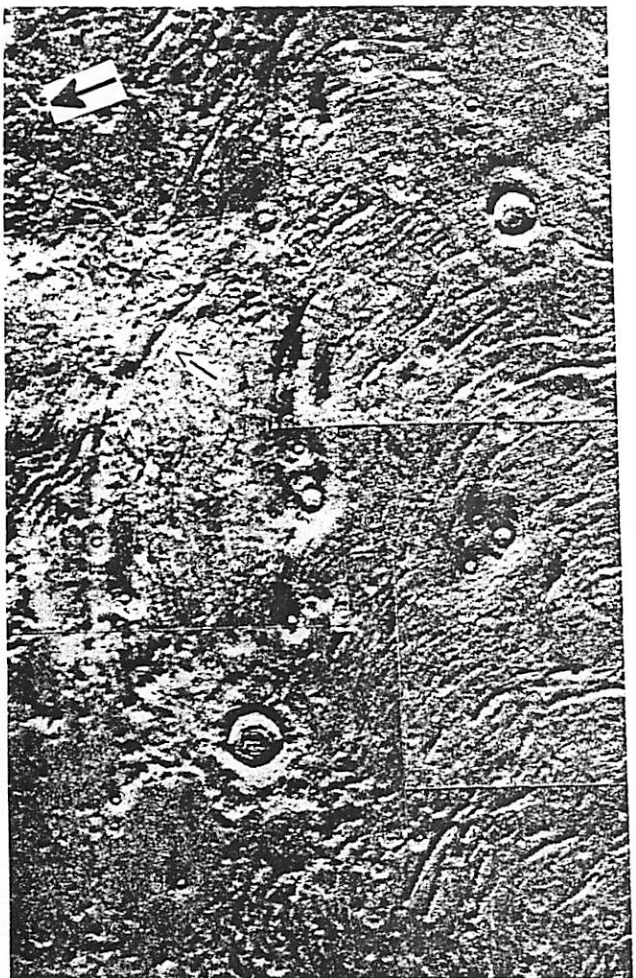
Glaciolacustrine features -- meltwater fed lacustrine deposition landforms include <u>outwash deltas</u>, <u>subaquatic outwash</u> from underwater tunnel mouths, <u>strandlines</u>, <u>bars</u>, <u>spits</u>.

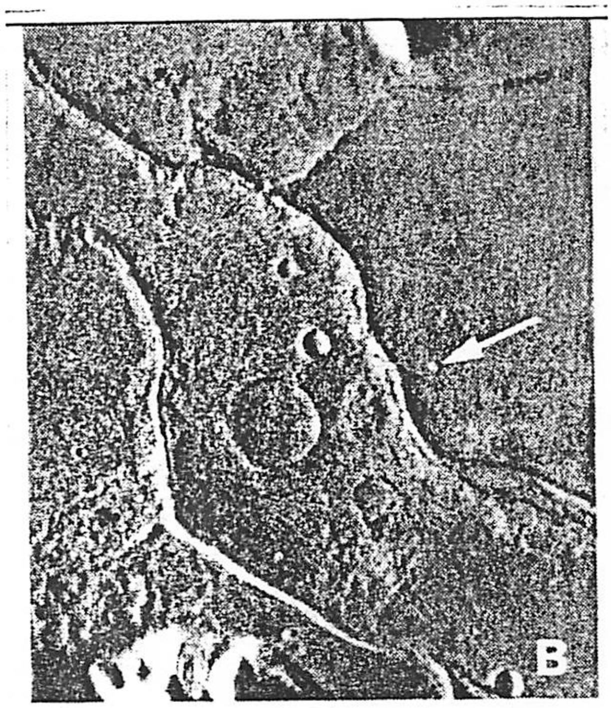
<u>White Mountains</u>

In the White Mountains most of the depositional evidence for glaciation consists of glacial drift on valley floors, lateral and end moraines (see geologic map in Karen Meyers and Cynthia Phillips' handout "Glacial History, White Mountains to the world") and erratics. There are also glaciofluvial and glaciolacustrine deposits.

<u>Planetary Connection</u>

Possible glacial deposition features identified on Mars including eskers, kettles, and moraines.





References

Flint, R.F. and Skinner, B.J., Physical Geology 2nd ed., John Wiley and Sons, New York, 1977.

Goldthwait, R.P., Classification of glacial morphologic features, in Goldthwait, R.P. and Matsch, C.L., Eds., Genetic Classification of Glacigenic Deposits, A.A.Balkema Publishers, Rotterdam, 1988.

Kargel, J.S. and Strom R.G., Ancient Glaciation on Mars, Geology, **20**, pp. 3-7, 1992.

Kargel, J.S., Baker, V.R., Begét, J.E., Lockwood, J.F., Péwé, T.L., Shaw, J.S., Strom, R.G., Evidence of ancient continental glaciation in the Martian northern plains, JGR, **100**, pp.5351-5368, 1995.

Leet, L.D., Judson, S., and Kauffman, M.E., Physical Geology 6th ed., Prentice-Hall, Inc., Englewood Cliffs, N.J., 1982.

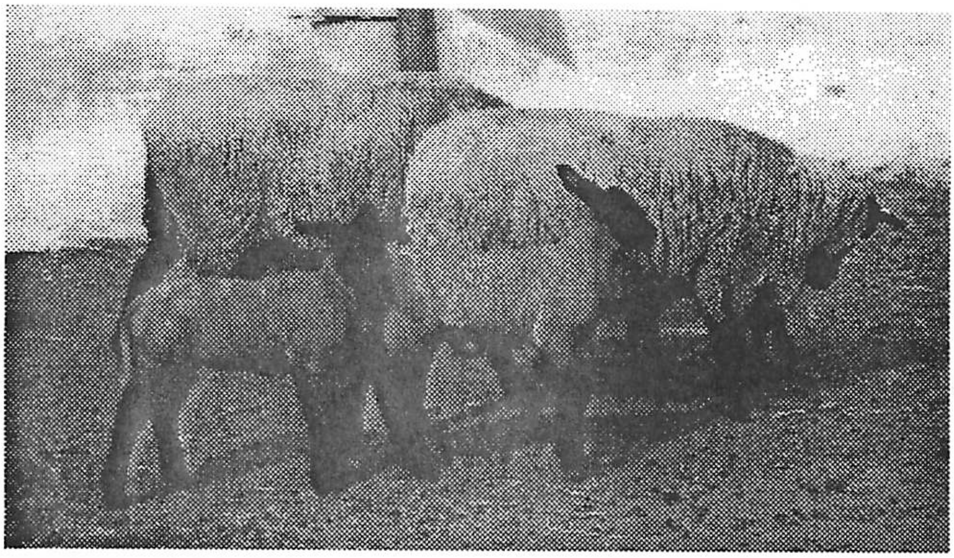
Merrill, R.K. and Péwé, T.L., Late Cenozoic geology of the White Mountains, Arizona, Special Paper #1 -- State of Arizona, Bureau of Geology and Mineral Technology, 1977.

Péwé, T.L., Merrill, R.K., Updike, R.G., Glaciation in the San Francisco Peaks and the White Mountains in Landscapes of Arizona: The Geological Story, 1984, Smiley, T.L, Nations, S.D., Péwé, T.L., Schafer, J.P., Eds.

Sugden, D.E. and John, B.S., Glaciers and Landscape: A Geomorphological Approach, Edward Arnold Ltd. London, 1976.

Sheep Crossing Formation

Greg Hoppa



The Sheep Crossing formation is a sedimentary feature that formed 8.6 million years ago on the lower slopes of Mount Baldy. The formation has been mapped over 600 km^2 and has a patchy distribution presumably due to erosion. In most cases the original surface has not been preserved except where it has been capped by basalt. This formation consists of two members, Campground Member and Marshall Butte Member.

The Campground Member is only a few meters thick and is named after the Sheep Crossing Campground where we will be staying on the first night. Poorly stratified gravel and sand are the primary components of this unit, however boulders as large as 6 meters can be found within.

The Marshall Butte Member is nearly 100 m thick and is named after a hill on the southwest side of Mount Baldy. Unlike the Campground Member the Marshall Butte unit is well stratified. Figure 1. shows the cross-section of the Sheep Crossing formation.

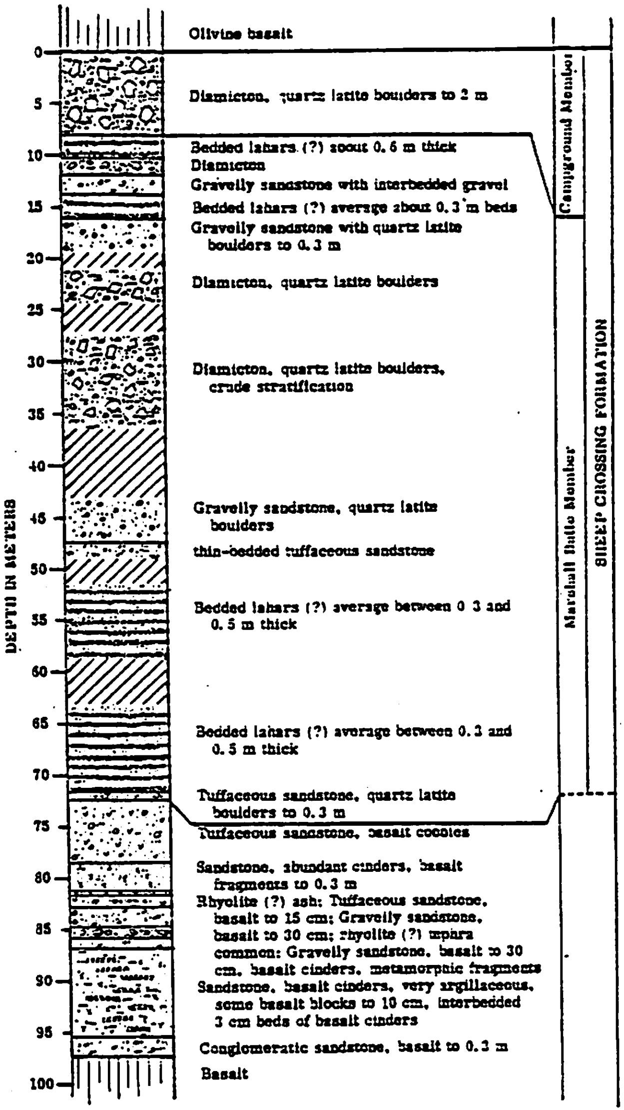


Figure 1.

Origin:

The Sheep Crossing Formation is believed to have formed by the flow of fragmented material that was initiated on the upper slopes of Mount Baldy. The extent of these flows are affected by topography and gravity. Flow rates can be as low as 10 m/s for movement of cool material due to creep and wash., however for hot fluids the velocities can approach 131 m/s. The flow of hot material is commonly referred to as nuée ardentes, or glowing avalanche. Observations of volcanic ash and dust within the Marshall Butte Member suggest that this unit was formed while Mount Baldy was still active. The absence of primary tephra within the Campground Member suggests that this was formed shortly after the volcano became inactive. Figure 2. shows a sketch of Mount Baldy as it may have appeared during the Miocene time.

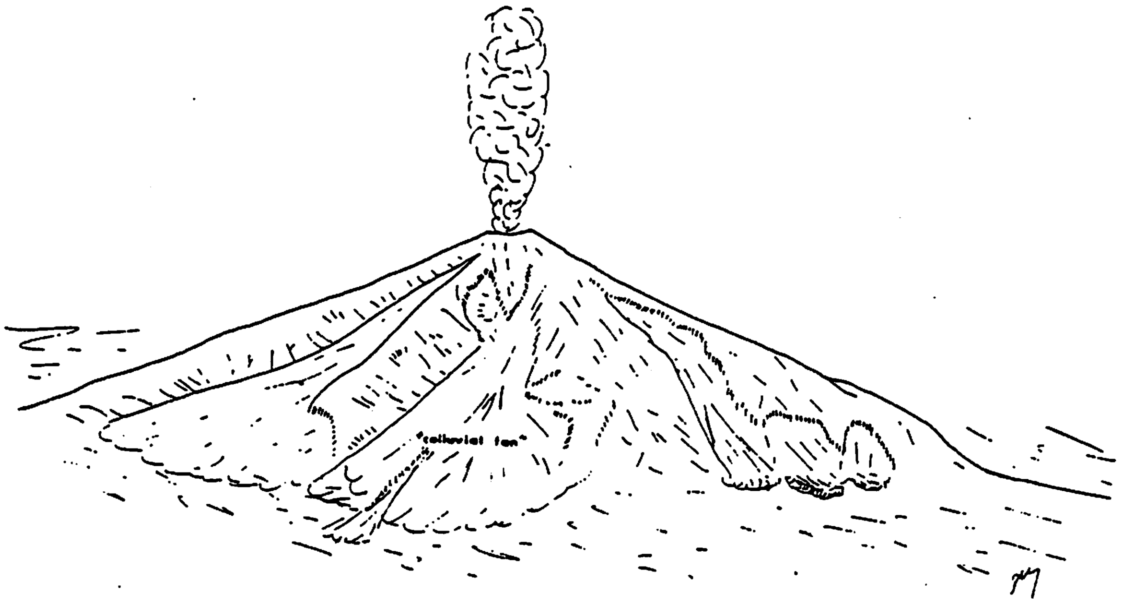


Figure 2.

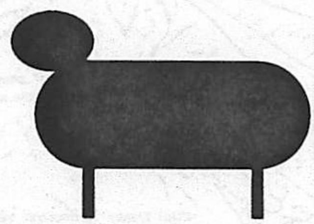
Due to the high fluidity of the soil during its movement down the slope of Mount Baldy, these flows were capable of carrying a wide distribution of material. The deposition of clay, silt and gravel is very similar to glacial till. Therefore the local topography, age and the distribution of the deposit are necessary to distinguish Sheep Crossing Formation from glacial till.

Features similar to Sheep Crossing Formation have been observed, as large fans in the Sinaqua Formation for the San Francisco peaks in northern Arizona. These colluvial features have also been observed on the slopes of the volcanos near Mexico City and on Irazu Volcano, Costa Rica.

References:

Melosh, H. J. "Dynamical weakening of faults by acoustic fluidization" *Nature,* vol. 379, p. 601-605. 1996.

Merrill, Robert K. and Pewe, Troy L. *Late Cenozoic Geology of the White Mountains Arizona.* p. 17-23. 1977.



From *Better Homes and Gardens* New Cook Book.

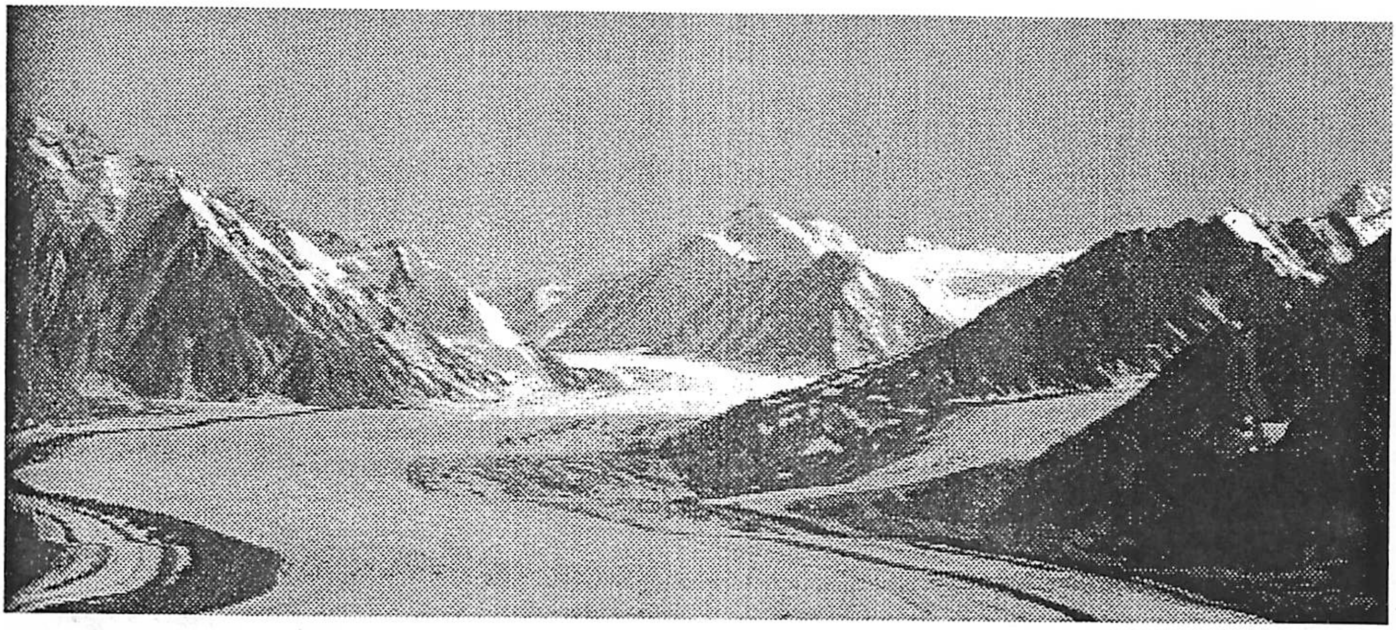
Lamb Chops with Honey-Mustard Glaze:

Trim fat from 4 *lamb loin chops*, cut 1 inch thick. If desired, sprinkle with salt and pepper. Place chops on the unheated rack of a broiler pan. Broil 3 inches from the heat for 5 minutes. Turn; broil 5 minutes more for medium. Meanwhile, combine 2 tablespoons *honey* and 4 teaspoons *Dijon-style mustard*. Brush each side of chops with honey mixture. Broil 1 minute more on each side. Brush any remaining honey mixture over chops before serving. Sprinkle with 1 tablespoon snipped parsley and 1 tablespoon finely chopped walnuts or pecans, if desired. Makes 2 servings.

Glacial Erosional Features

A Virtual Tour

with your abrasive host, Barbara Cohen



Glaciers erode rock in two ways: plucking and abrasion.

Plucking: ice at the bottom or side of a glacier can melt and surround particles in the rock or soil. The expansion of the water as it refreezes pries particles loose. These particles can then become entrained in the glacier and be carried away. Particles here does not just refer to small bits of dirt. Huge boulders are known to be carried off this way!

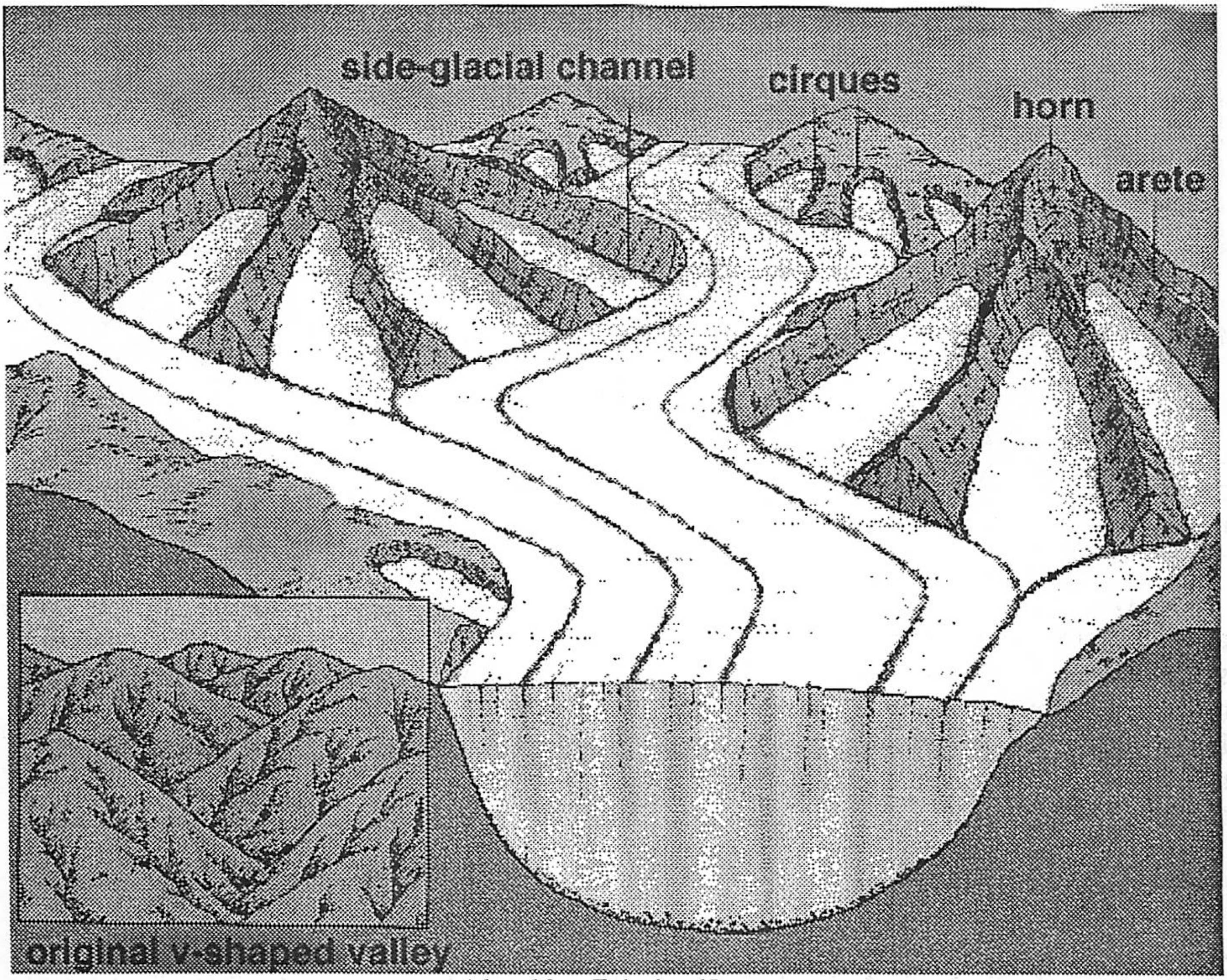
Abrasion: The bottom of the glacier carries a load of rock particles, just as rivers do. These particles scour the bedrock muck like sandpaper. Some surfaces get sanded to a smooth shine, but some surfaces will show glacial striations. Glacial striations are used to reconstruct flow direction. The rock that is pulverized in this manner is called rock flour. Rock flour often gets entrained in the streams underneath the glacier and carried out. So much flour can be generated that often the outflow streams have the appearance of skim milk.

Glacial Jargon

U-shaped valleys or **glacial troughs**. Glaciers take the path of least resistance, which often means utilizing existing streambeds. The streambeds are originally v-shaped due to downcutting by a line, but glaciers broaden the bottom and sides, creating a characteristic u-shaped profile.

Hanging valleys and **truncated spurs**. Glaciers in a valley network don't erode at the same rate. When a glacier erodes the main valley more than the tributaries, the main valley becomes deep and the tributaries remain high. The land in between the tributaries also gets cut off, leaving triangular spurs between hanging valleys.

Side-glacial channels. Glaciers take up the space where runoff once went. This water will flow in the crevice between the glacier and the side of the valley. The channel erodes just as normal stream channels, but is located high up on the valley wall. When the glacier retreats, these channels appear as ledges or terraces on the valley wall.

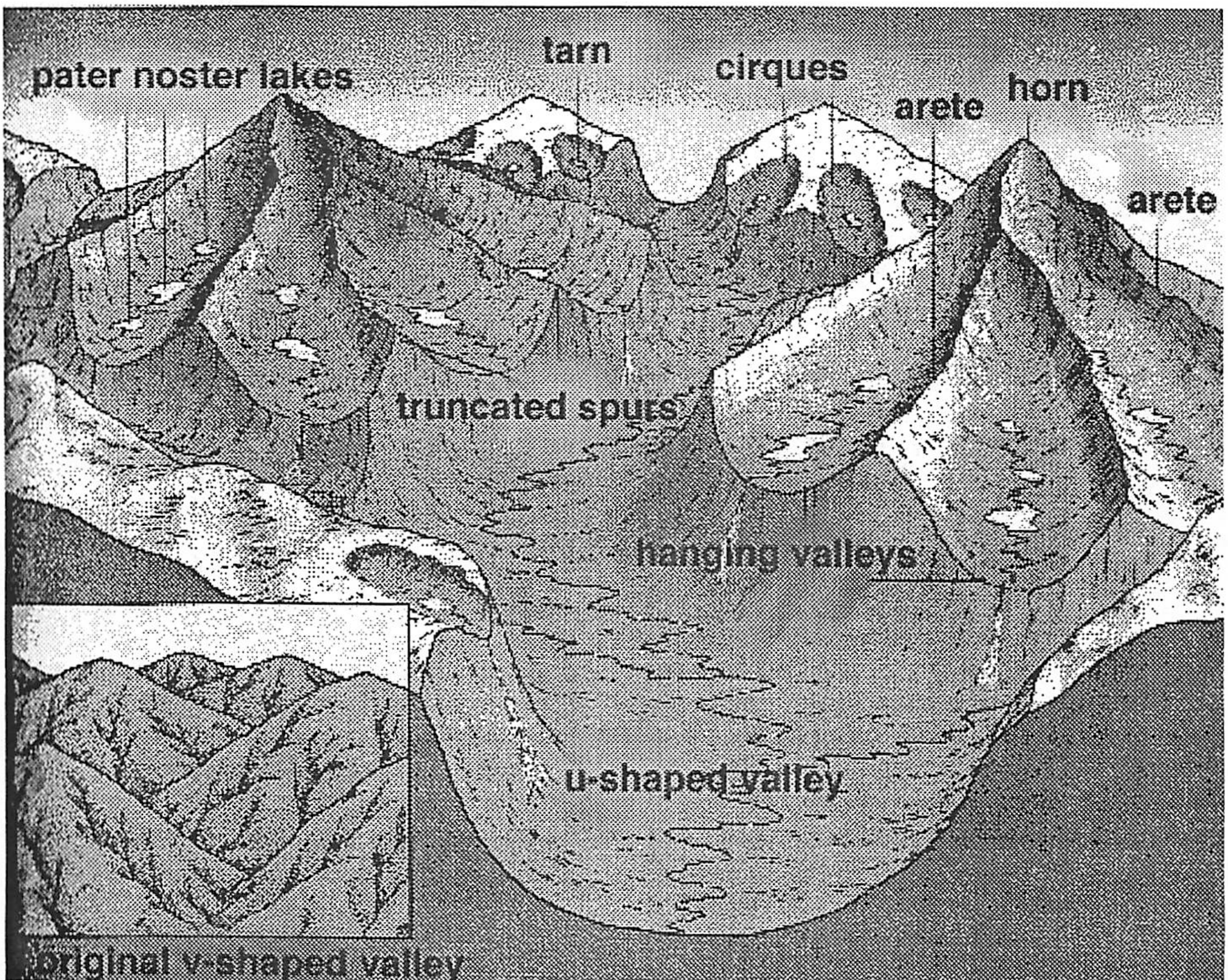


Adapted from Tarbuck and Lutgens

Cirques and **cols**. At the head of the glacier where it is accumulating snow and ice, much erosion occurs. Bowl-shaped depressions, or cirques, get cut out of the mountain which are deep on three sides but open on the downvalley side. When two glaciers accumulate near each other, but flow in opposite directions, their respective cirques may cut toward each other and eventually meet, forming a col. Cols are often used as mountain passes.

Horns and **aretes**. Mountain glaciers flow down from a mountain and abrade its sides. The mountain often takes on a very steep aspect, with polygonal sides. The most famous horn is the Matterhorn in the Swiss Alps. The polygonal sides are separated by steep and sharp aretes, or ridges, which were the separations between the valleys in which the glacier flowed.

Roches moutonées. Usually found in continental areas, these are small bumps of bedrock that are abraded on the side facing the ice sheet and plucked on the opposite side. The asymmetrical shape tells in which direction the glacier flowed. 

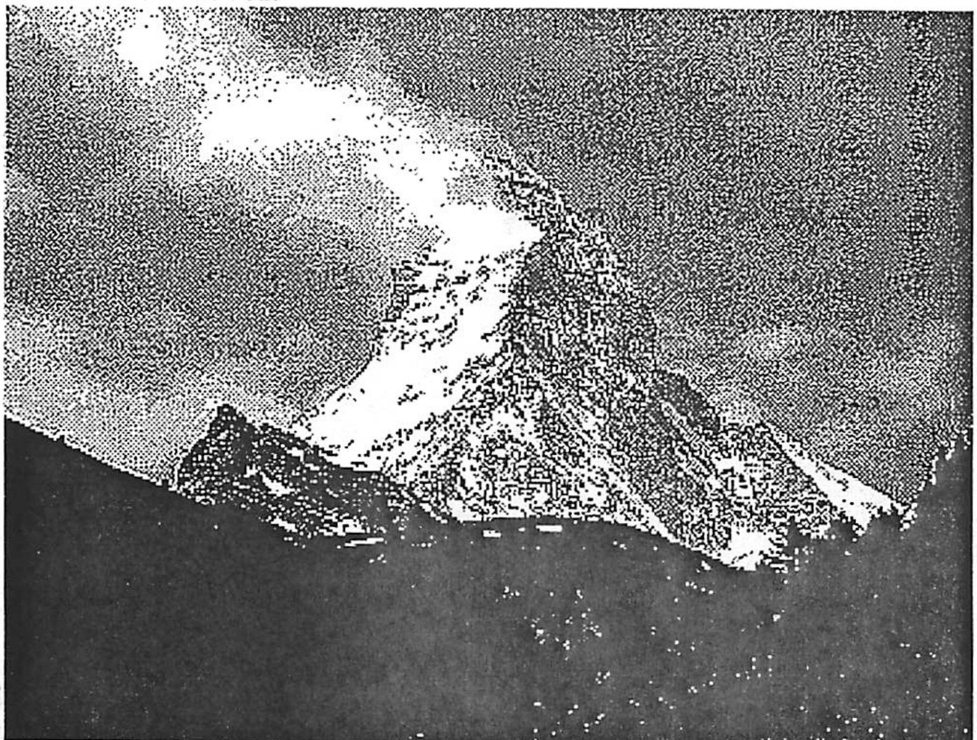


Adapted from Tarbuck and Lutgens

More Glacial Jargon

Tarns and **pater noster lakes**. Water often fills glacial depressions. Tarns form in cirques and pater noster lakes form in strings down valleys, looking like beads from overhead.

Fjords. When glaciers retreat and sea level rises again, the sea will drown glacial troughs in much the same way as estuaries are formed. These drowned glacial troughs are called fjords, as seen along the coasts of Norway, New Zealand, Alaska, etc. Fjords are often quite deep, sometimes exceeding 1000 meters. The dramatic depth is caused partly by the rise in sea level, but partly because of a neato property of glaciers. Unlike the erosion done by rivers, glaciers do not have a baseline controlled by sea level. Therefore, glaciers can cut to levels far below sea level.



The Matterhorn, one of the best-known examples of Alpine glacial erosion.

The rates of glacial erosion are highly variable among areas of the world, glacial periods, and even among nearby glaciers. Erosion rates depend on

- rate of glacial movement
- thickness (weight) of the ice
- shape, abundance, and hardness of rock embedded in the ice
- erodability of the surface

Periglacial Processes And Features

What is "periglacial"? The problem is that there are two different meanings to the term periglacial. The original, strictly defined term, refers to the area immediately surrounding a glacial area. More recently, however, it has been used to refer to a more general phenomenon, terrain affected by intense cold (permafrost), whether or not there have been any glaciers in the area. The term geocryology is preferred by some, but periglacial is much less cumbersome than geocryological.

In either case, glacial processes are specifically omitted, though some glacial processes technically leave their mark on the surrounding terrain instead of within the glacial sheet: outwash plains, for example.

Processes

The most important and pervasive periglacial process is frost action, more specifically the action of the frost-thaw cycle on different subjects. This includes frost wedging, frost heaving, frost cracking, and frost sorting. The basic action is simple: liquid water seeps through pores and joints, then freezes. Upon freezing, it expands.

Frost wedging (also congelifraction, gelifraction, frost riving, frost shattering, or frost splitting) is when the expanding ice pries materials (commonly rock) apart. Frost wedging produces angular fragments, ranging in size from fines to house-sized blocks. Huge piles of talus produced from frost wedging are often found in periglacial regions.

Since the pressure generated by expanding ice crystals is at right angles to the freezing isotherm, which is usually more or less horizontal in soils, frost action in such soils tends to push upwards. This process is known as frost heaving, and can push buried blocks or small stones above the surface. Two proposed mechanisms for 'upfreezing' of stones are frost-pull and frost-push (see figures 1 and 2). Frost heaving tends to rotate buried objects such that their long axis is oriented vertically (see figure 3).

After freezing (and hence expanding), ice can be cooled further, resulting in contraction, and what is called frost cracking. Liquid water can enter these cracks, resulting in an ultimate expansion and growth of the ice into ice wedges. If the area later thaws completely, the ice wedge melts, leaving a cavity which is filled in by loose material. This loose material forms a cast of the wedge. Such ice wedge casts are one of the only accepted signs for former permafrost in an area. Frost cracking can result in linear or polygonal cracking on the surface, similar to dessication cracks.

Frost sorting can occur through many freezing processes, though the specifics are not entirely understood. It is known from laboratory experiments that as a freeze propagates through a soil, finer particles can be pushed ahead of the isotherm, while coarser particles become trapped. On a larger scale, frost heaving of individual stones seems to work more quickly for larger stones, lifting them to the surface faster than smaller ones.

Features

The most common periglacial frost-action features include patterned ground, stone pavements, periglacial involutions, palsas and pingos. Periglacial mass-wasting features include boulder streams and protalus ramparts.

Patterned ground is a general term including circular, polygonal, and striped patterns. Unsorted patterns involve tend to be uniform within a given unit, but sorted patterns are marked by coarse, stony borders and interior fines. Circles and polygons occur on flat ground, primarily. Stripes seem to occur on slopes that would otherwise qualify for circles or polygons.

The origin of patterned ground is perhaps best described as complicated. It is believed that a number of different processes may contribute to similar endforms, and that one process can produce multiple endforms. In general, it is felt that there are separate patterning and sorting processes (with a 'slope process' thrown in as well).

Stone pavements are similar to desert pavements, and are believed to be formed from upfreezing of rocks through frost heaving and rotation while elevated, followed by infilling of fines, perhaps. Stone pavements tend to be made of larger stones than desert pavements.

Periglacial involutions are marked by meandering, warped beds and apparently random interpenetrations of same. This is explained as being simply due to the variety of frost action proccesses acting along the beds.

Palsas and pingos are both hills built around ice. Palsas are largely peat, with interior ice lenses. Pingos are larger, not primarily peat, and with a massive ice core. Both are thought to grow by growth of the interior ice. Pingos are commonly remotely identified by their collapse.

The intensive fracturing action of frost wedging often results in high amounts of mass-wasting in periglacial environments. Taluses are common, as are other features known as block fields, boulder or block streams, and protalus ramparts. Block fields and streams tend not to have a readily recognizable sheer face at their head, unlike taluses. Protalus ramparts are formed when piecemeal mass-wasting drops debris onto a snowbank, guiding it to the base of the snowbank.

The White Mountains

The most mentioned periglacial features in literature on the White Mountains are protalus ramparts, which hopefully we'll get to see. Boulder streams are also mentioned. Low mounds of uncertain origin are also mentioned. Unfortunately, the freshest features are those associated with the Mt. Ord glaciation, while we're going to be at Baldy.

The Planetary Connection

Mars.

Okay, okay. Mars is the one place where we see evidence for permafrost, or even just a freeze-thaw cycle. In addition to a number of presumed pingos, patterned ground is the primary periglacial feature on Mars. The giant polygons, so frequently discussed in the context of Red Lake Playa, are similar to the polygons observed in periglacial regions, though much bigger. Smaller polygons, about the size of periglacial polygons on Earth, are also observed.

FIG 1

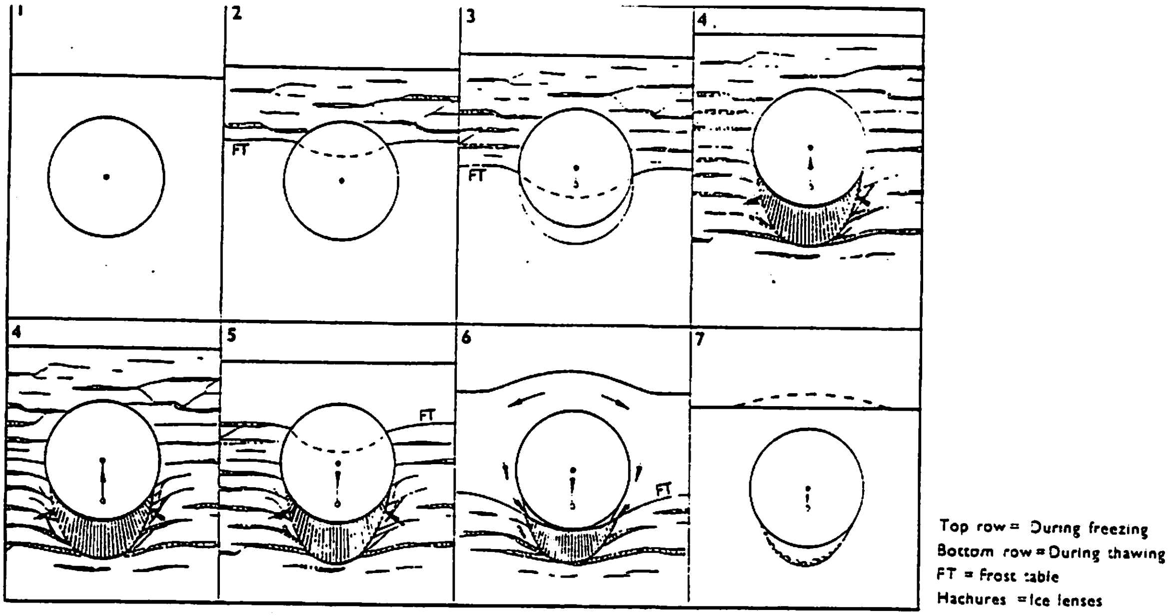
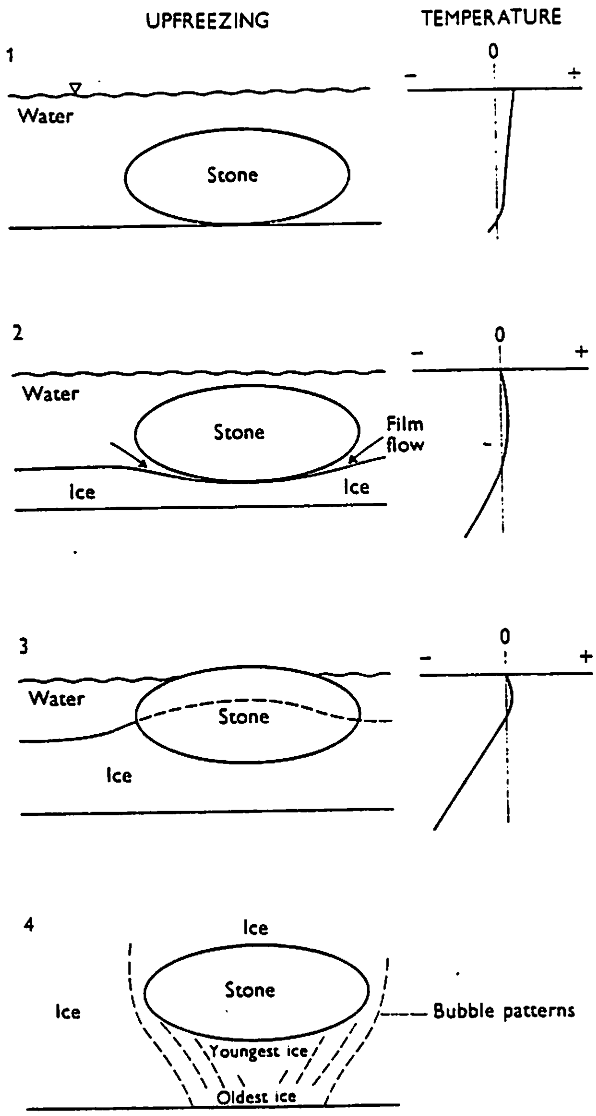


FIG 2



4.17 Uplift of stone by bottom-upward freezing. Laboratory experiment by *J. R. Mackay, 1977*

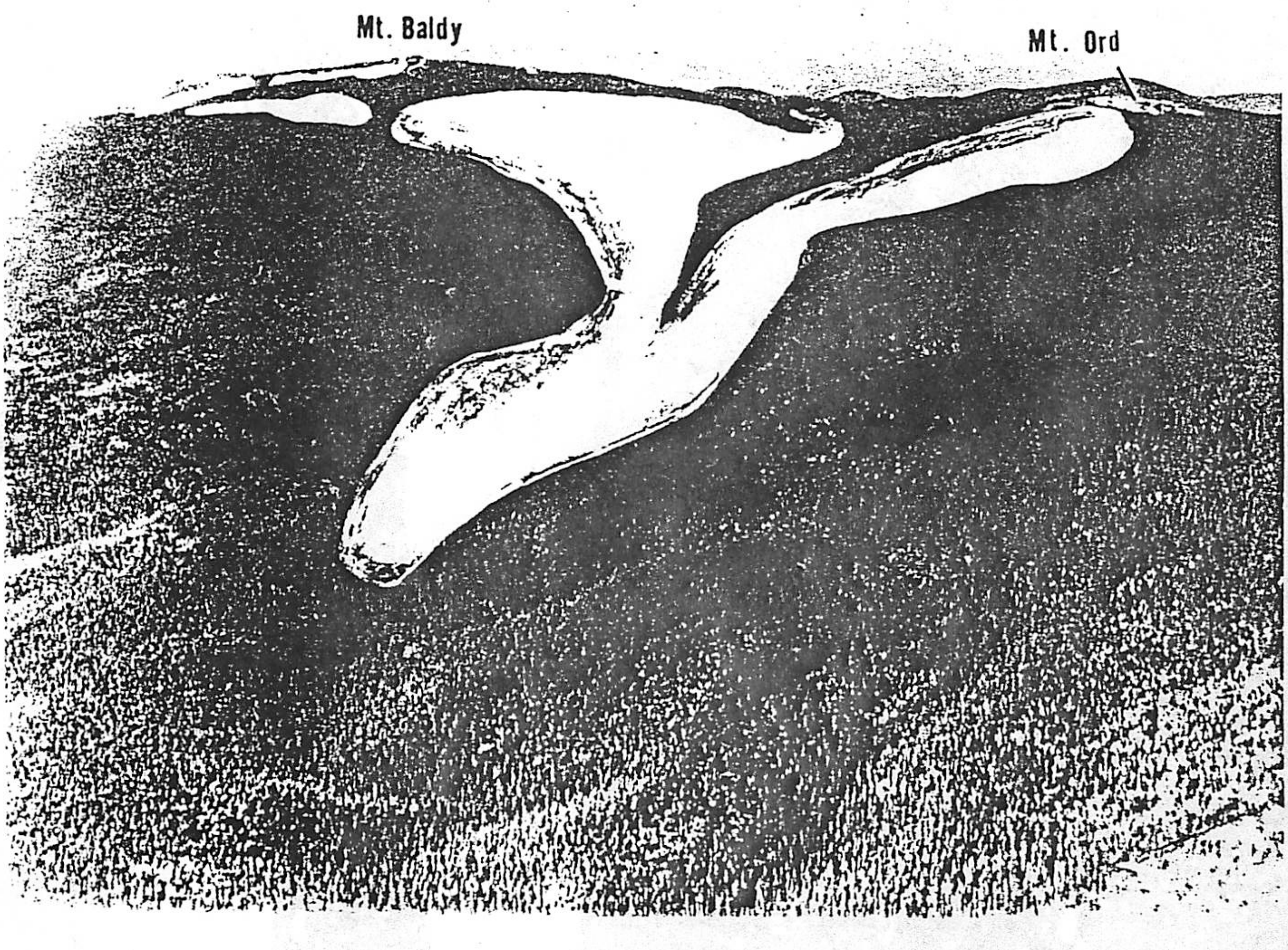
FIG 3

30

GLACIAL HISTORY: WHITE MOUNTAINS TO THE WORLD

PARTNERS IN CRIME:

CYNTHIA PHILLIPS: WHITE MOUNTAINS
KAREN MEYERS: THE WORLD



Frontispiece.—The White Mountains from the north as they might have looked during Purcell time.

The Four Late Quaternary Alpine / Valley Glaciations in the White Mountains

Glaciation	*Purcell*	*Smith Cienega*	*Baldy Peak*	*Mount Ord*
Time • Wisconsinan glaciation started about 100,000 - 125,000 years ago	• Pre-Wisconsinan (Illinoian) • between 100,000 and 212,000 years ago	• Early Wisconsinan	• Late Wisconsinan	• Early to mid Holocene • C-14 dating of charcoal in moraine: 3000 years old • other dating methods (talus development, moraine preservation) • likely pd. of glaciation 6000 to 3000 years ago
Remaining features	• U-shaped valleys • subdued moraines • scattered erratics • abrupt change from U-shaped glacial valley to V-shaped canyon represents maximum extent of glaciation	• moderately subdued moraines • fluvial and lacustrine deposits • recessional moraines common	• Sharp-crested moraines in higher valleys • well-preserved • Some moraines are multiple, have kettles preserved on them	• Single, well-preserved, steep-fronted, very bouldery moraine • 3 m high • Deposit of colluvium 1.8 m deep behind moraine
Glacial Extent	• Glacier occupying valley of W. Fork of Little Colorado River was about 7 km long	• On W.Fork of Little Colorado River, glacier was about 3.5 km long	• Two glaciers present on W. Fork of Little Colorado River, each 1.3 km long	• Single Glacier was 0.2 km long
Glaciated snow line • present snowline = 3900 m • Mt. Baldy = 3475 m	3140 m	3190 m	3260 m	3380 m

Other interesting information:

- Climatic differences in White Mountain area
  - Mean annual temperature during periods of glaciation was 5-6°C lower than today
  - precipitation was 20-25% higher than today

- Often difficult to distinguish between glacial till and till-like volcanic deposits due to volcanic mudflows and other processes
  - many volcanic deposits in White mountain area first erroneously attributed to glaciation

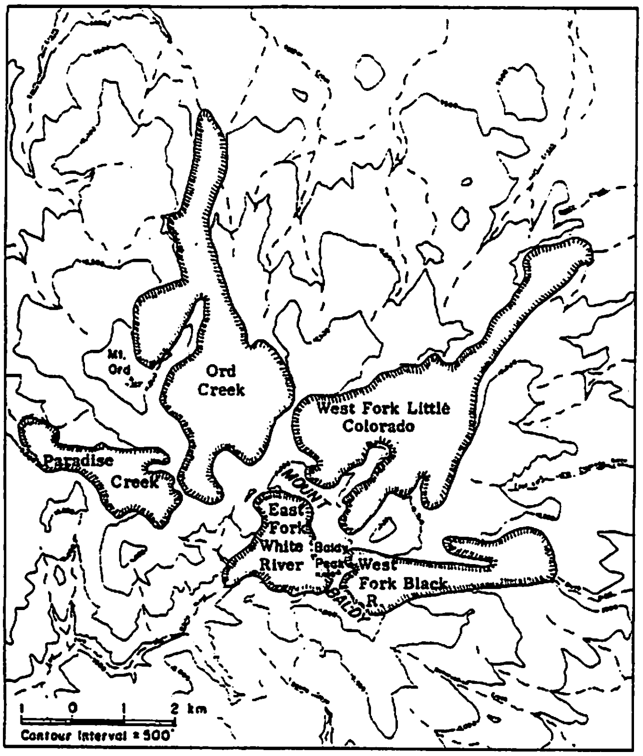


Figure 30.—Extent of glaciers during Purcell time in the White Mountains.

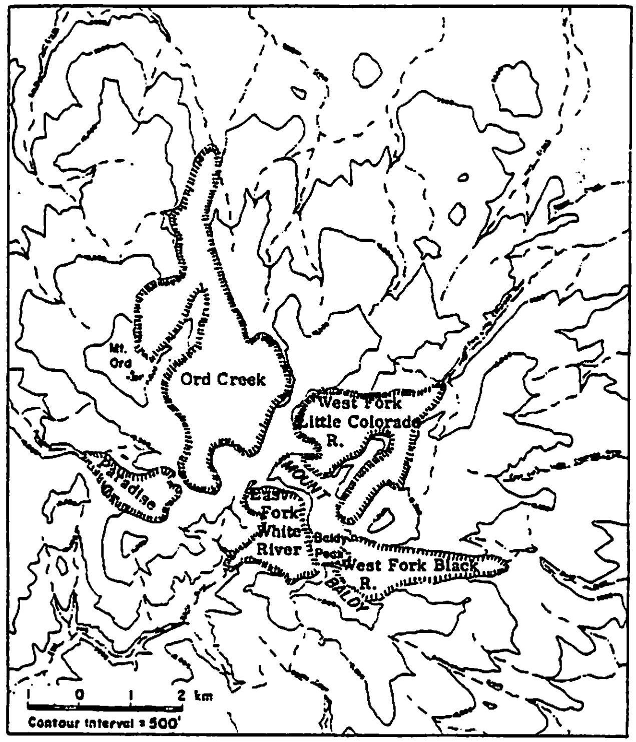


Figure 31.—Extent of glaciers during Smith Cienega time in the White Mountains.

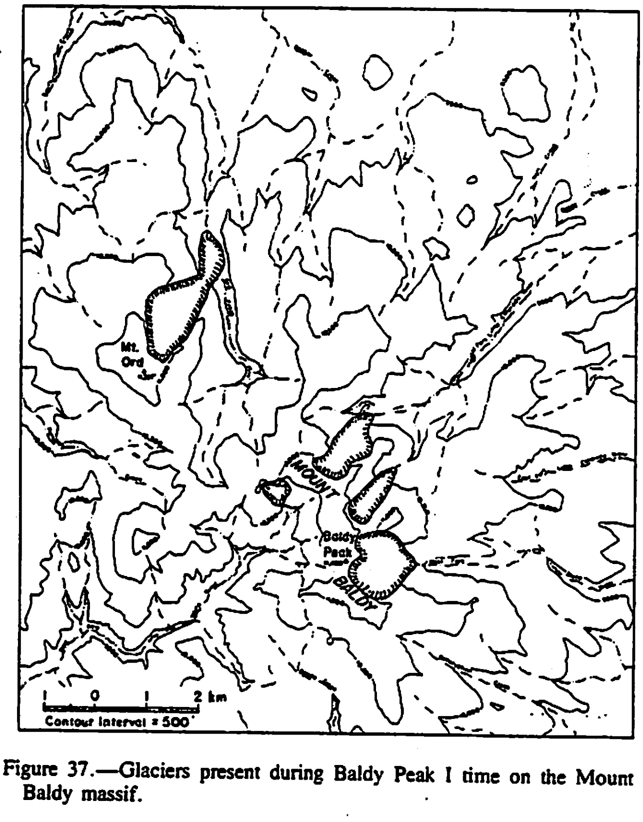


Figure 37.—Glaciers present during Baldy Peak I time on the Mount Baldy massif.

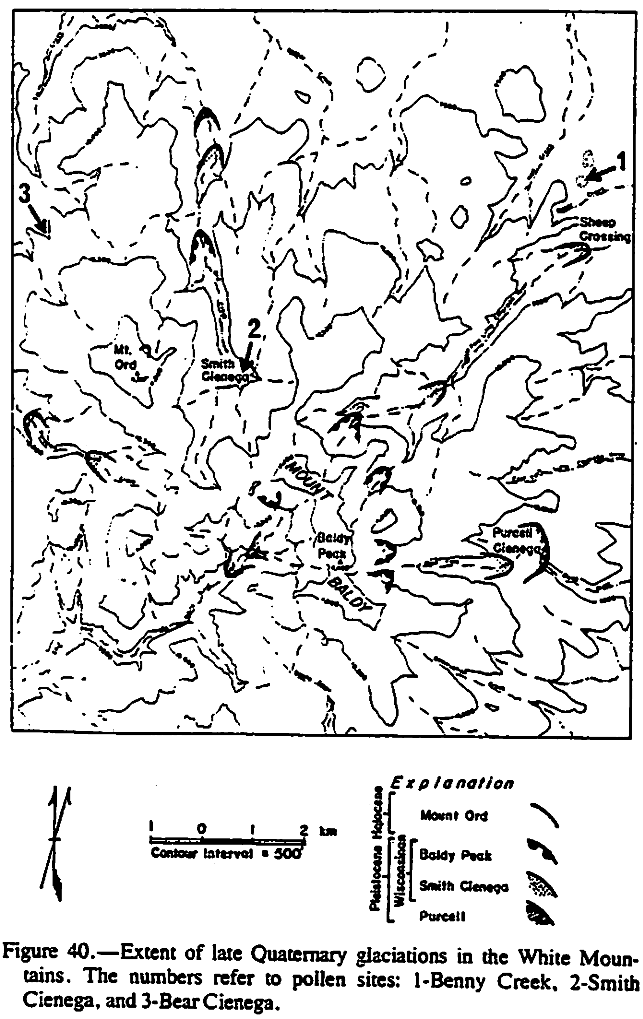
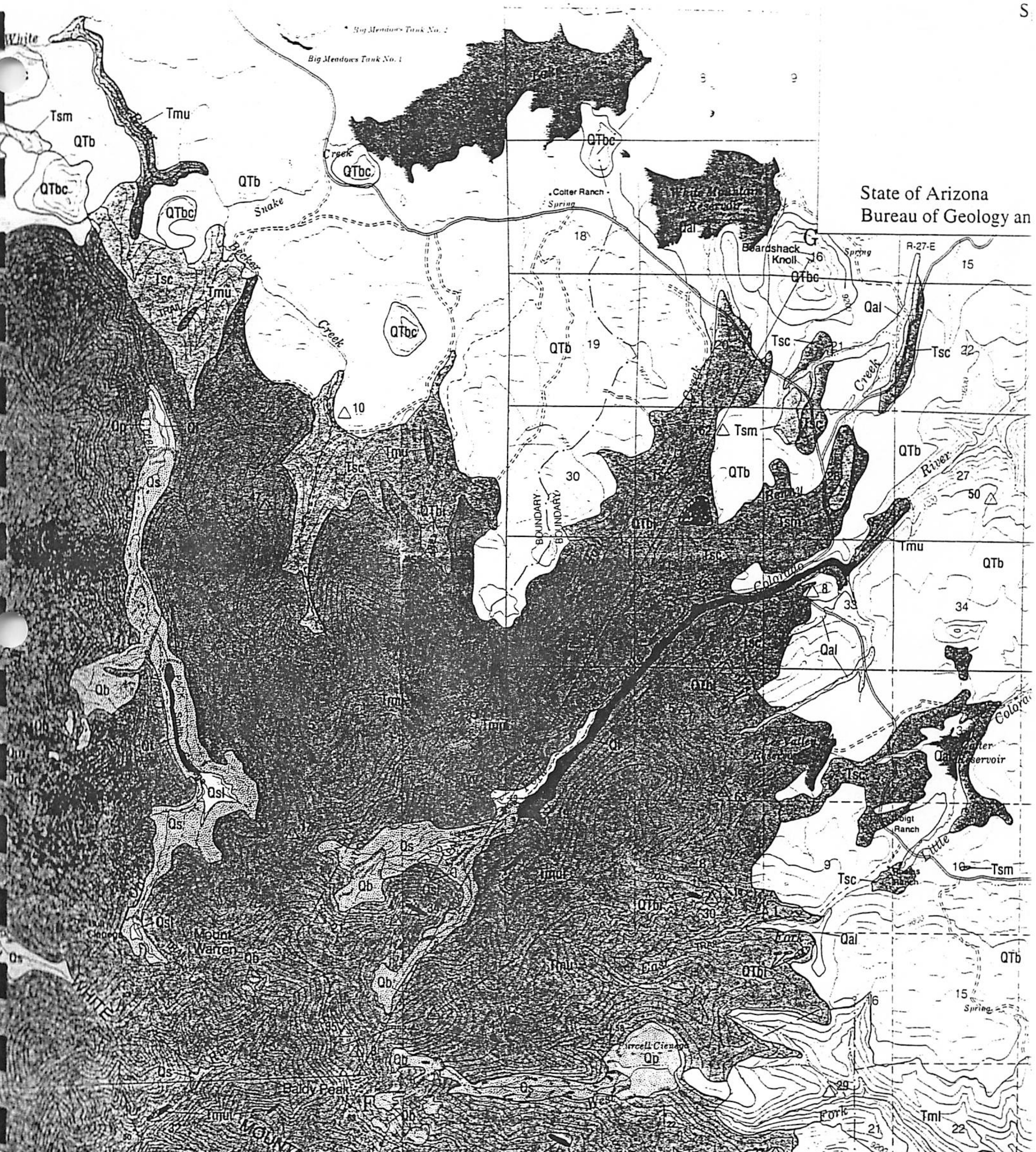


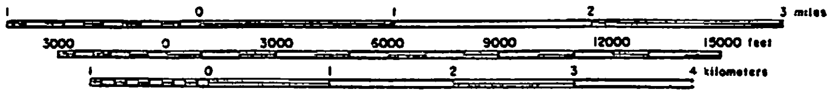
Figure 40.—Extent of late Quaternary glaciations in the White Mountains. The numbers refer to pollen sites: 1-Benny Creek, 2-Smith Cienega, and 3-Bear Cienega.


State of Arizona
Bureau of Geology an
Big Meadows Tank No. 2
Big Meadows Tank No. 1
White
Tsm
QTb
QTbc
Tmu
Creek
Snake
Becker
Colter Ranch
Spring
Boardshack
Knoll
R-27-E
Qal
Tsc
Tml
Qs
Qb
Qsl
Qp
River
Colorado
BOUNDARY
Mount
Warren
Baldy Peak
Purcell Cienega
MOUNTAINS
WHITE
Voigt
Ranch
Little
Fork
East
Reservoir
Thompson
Spring

GEOLOGY OF THE WHITE MOUNTAINS APACHE COUNTY, ARIZONA

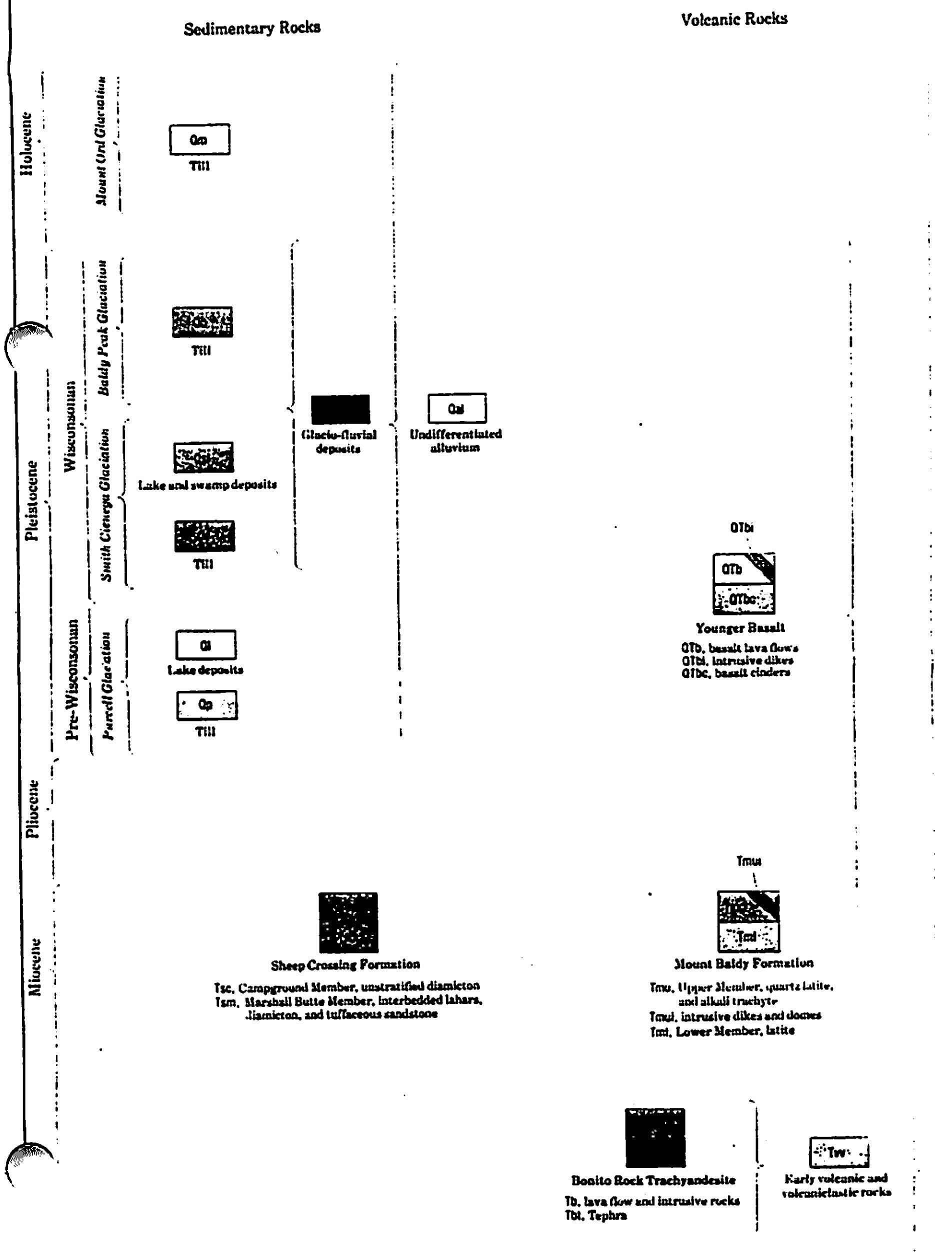
by
Robert K. Merrill
and
Troy L. Péwé
1973

SCALE 1 : 48000

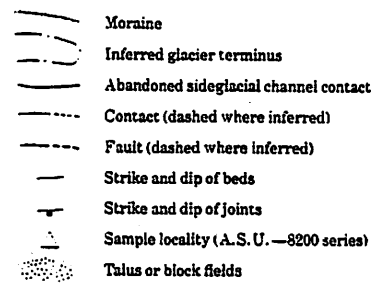


CONTOUR INTERVAL 80 FEET
DATUM IS MEAN SEA LEVEL

EXPLANATION



SYMBOLS



The Rest of the World (or at least the Northern Hemisphere)

Southwestern United States

Correlation of late Quaternary glacial events in the southwestern United States

	White Mountains	San Francisco Peaks	Sierra Nevada	Rocky Mountains
Early Holocene	Mount Ord[1]		Recess Peak[1]	Temple Lake[1]
Late Wisconsinan	Baldy Peak[1]	Snowslide Spring[1]	Tioga[2]	Pinedale[1]
Early Wisconsinan	Smith Cienega[1]	Core Ridge[1]	Tahoe[1]	Bull Lake[1]
Late Illinoian (Pre-Wisconsinan)	Purcell[1]	Lockett Meadow[1]	Mono Basin[2]	Sacagawea Ridge[1]

[1] From Merril and Péwé, 1977
[2] From Richmond 1986

North America

Two main ice sheets are recognized in North America:
The **Laurentide Ice Sheet** was the major North American ice sheet
The **Cordilleran Ice Sheet** covered western Canada and the northwestern United States
-generally, the region west of (and including) the Rocky Mountains

Northern Hemisphere

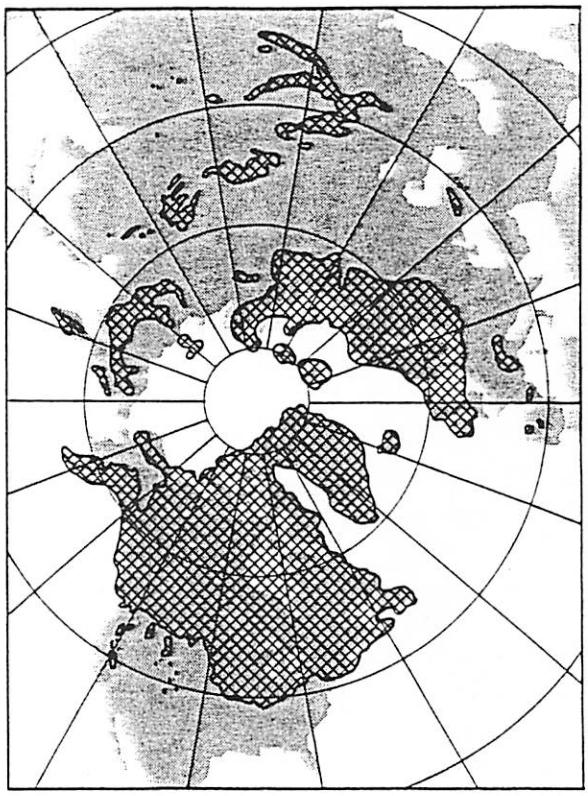
Alternative names for the Late Pleistocene glacial period

United States and Canada	United Kingdom	Germany	European Alps	Former USSR
Wisconsinan	Devensian	Weichselian	Würm	Valdai

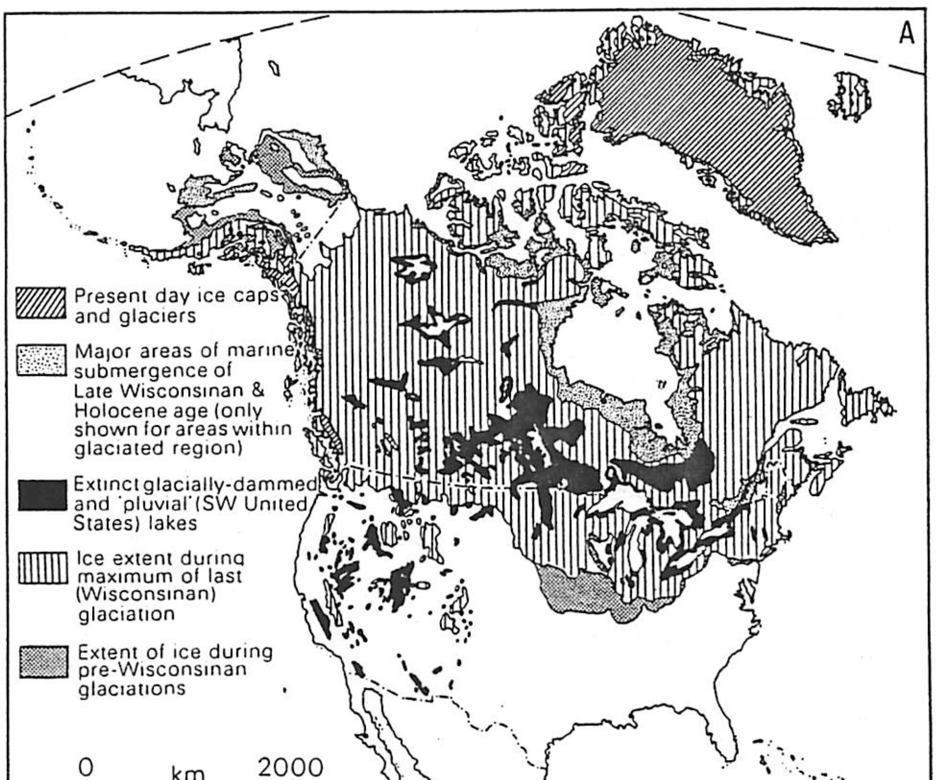
Formal Geochronologic Units		Informal Time Divisions			Age (yr)
	Holocene		Post-Pleistocene		
					10,000[1]
		Late Pleistocene	Wisconsin	Late Wisconsin	
					35,000[2]
				Middle Wisconsin	
					65,000[2]
				Early Wisconsin	
					79,000[2]
				"Eowisconsin"	
					122,000[2]
Quaternary	Pleistocene		Sangamon		
					132,000[2]
		Late middle Pleistocene	Illinoian	Late Illinoian	
					198,000[2]
				Early Illinoian	
					302,000[2]
		Middle middle Pleistocene	Pre-Illinoian		
					610,000[3]
		Early middle Pleistocene			
					788,000[4]
		Early Pleistocene			
					1,650,000[5]
Tertiary	Pliocene	Pre-Pleistocene			

[1] Arbitrary age assigned to the Pleistocene–Holocene boundary (Hopkins, 1975).
[2] Estimated astronomical age of correlated marine oxygen isotope stage boundary, interpolated from Figs 4 and 6–10 in Johnson (1982).
[3] 'Best estimate' K–Ar age of Lava Creek Tuff and Pearlette "O" volcanic ash bed (Izett, 1981).
[4] Astronomical age of the Matuyama–Brunhes magnetic polarity reversal (Johnson, 1982).
[5] Provisional radiometric age of the proposed Pliocene–Pleistocene boundary at the Vrica section, southern Italy (Aguirre and Pasini, 1984).

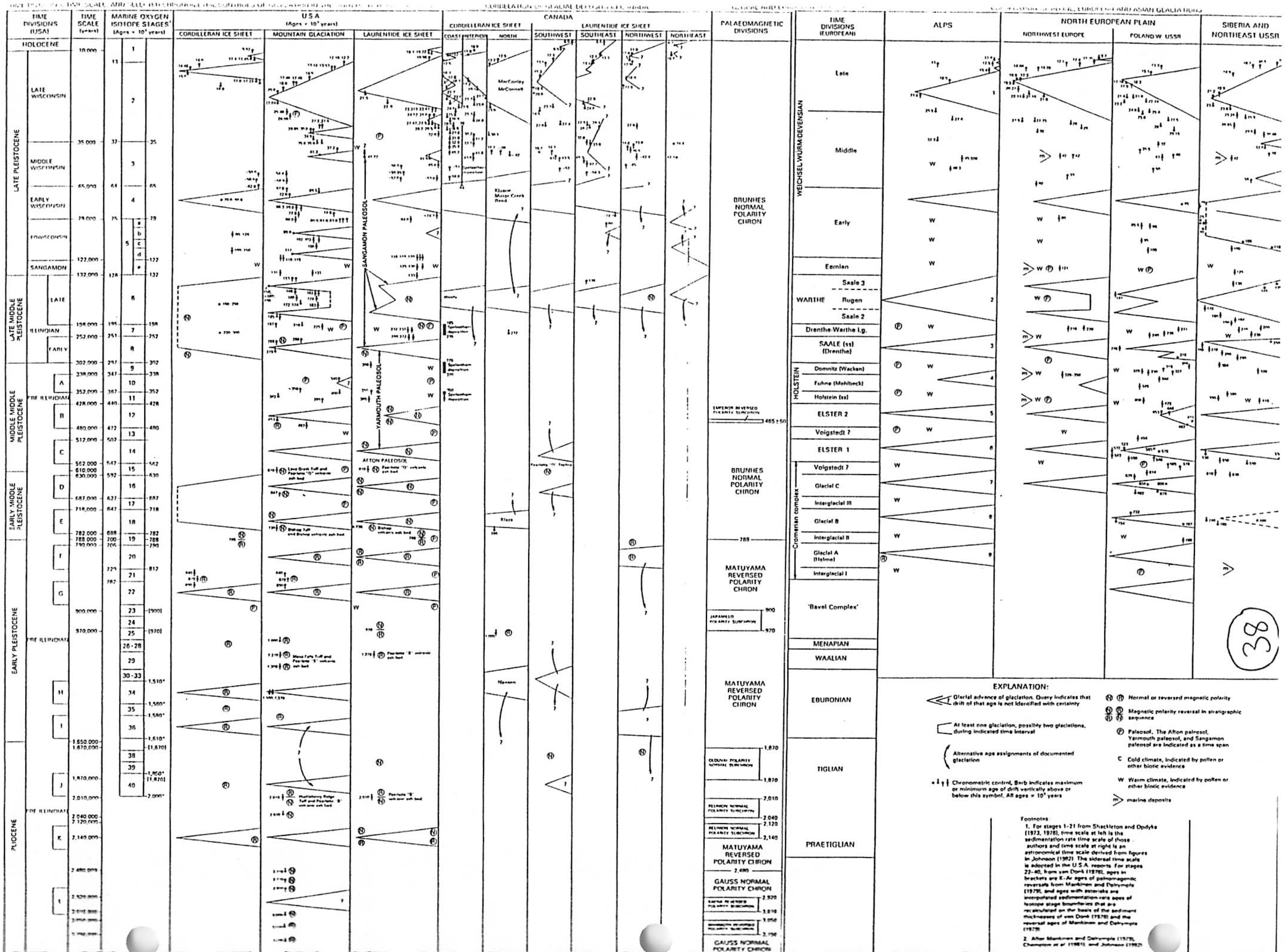
Provisional ages assigned to informal time division boundaries in the United States of America (From Richmond and Fullerton 1986).



Maximum extent of ice in the N. Hemispnere during the Quaternary. The map is generalized and many small areas are not shown (From Gray 1985).



Glacial limits in North America (from Lowe and Walker 1984).



TIME DIVISIONS (USA)
TIME SCALE (years)
MARINE OXYGEN ISOTOPE STAGES[1] (Ages × 10³ years)
USA
CORDILLERAN ICE SHEET
MOUNTAIN GLACIATION
LAURENTIDE ICE SHEET
CANADA
CORDILLERAN ICE SHEET
COAST INTERIOR
NORTH
SOUTHWEST
LAURENTIDE ICE SHEET
SOUTHEAST
NORTHWEST
NORTHEAST
PALAEOMAGNETIC DIVISIONS
TIME DIVISIONS (EUROPEAN)
ALPS
NORTH EUROPEAN PLAIN
NORTHWEST EUROPE
POLAND W. USSR
SIBERIA AND NORTHEAST USSR
HOLOCENE
LATE PLEISTOCENE
LATE WISCONSIN
MIDDLE WISCONSIN
EARLY WISCONSIN
SANGAMON
LATE MIDDLE PLEISTOCENE
ILLINOIAN
LATE
EARLY
MIDDLE MIDDLE PLEISTOCENE
PRE-ILLINOIAN
EARLY MIDDLE PLEISTOCENE
EARLY PLEISTOCENE
PLIOCENE
SANGAMON PALEOSOL
YARMOUTH PALEOSOL
AFTON PALEOSOL
BRUNHES NORMAL POLARITY CHRON
MATUYAMA REVERSED POLARITY CHRON
GAUSS NORMAL POLARITY CHRON
WEICHSEL-WÜRM-DEVENSIAN
Late
Middle
Early
Eemian
Saale 3
WARTHE
Rugen
Saale 2
Drenthe-Warthe I.g.
SAALE (ss) (Drenthe)
HOLSTEIN
Domnitz (Wacken)
Fuhne (Mehlbeck)
Holstein (ss)
ELSTER 2
Voigstedt ?
ELSTER 1
Cromerian complex
Voigstedt ?
Glacial C
Interglacial III
Glacial B
Interglacial II
Glacial A (Helme)
Interglacial I
'Bavel Complex'
MENAPIAN
WAALIAN
EBURONIAN
TIGLIAN
PRAETIGLIAN
EXPLANATION:
Glacial advance of glaciation. Query indicates that drift of that age is not identified with certainty
At least one glaciation, possibly two glaciations, during indicated time interval
Alternative age assignments of documented glaciation
Chronometric control. Barb indicates maximum or minimum age of drift vertically above or below this symbol. All ages × 10³ years
Normal or reversed magnetic polarity
Magnetic polarity reversal in stratigraphic sequence
Paleosol. The Afton paleosol, Yarmouth paleosol, and Sangamon paleosol are indicated as a time span
C Cold climate, indicated by pollen or other biotic evidence
W Warm climate, indicated by pollen or other biotic evidence
marine deposits
Footnotes:
1. For stages 1-21 from Shackleton and Opdyke (1973, 1976), time scale at left is the sedimentation-rate time scale of those authors and time scale at right is an astronomical time scale derived from figures in Johnson (1982). The sidereal time scale is adopted in the U.S.A. reports. For stages 22-40, from van Donk (1976), ages in brackets are K-Ar ages of paleomagnetic reversals from Mankinen and Dalrymple (1979), and ages with asterisks are interpolated sedimentation-rate ages of isotope stage boundaries that are recalculated on the basis of the sediment thicknesses of van Donk (1976) and the reversal ages of Mankinen and Dalrymple (1979).
2. After Mankinen and Dalrymple (1979), Champion et al. (1981), and Johnson (1982).

38

References

Bowen, D.Q. et al, 1986, Correlation of Quaternary glaciations in the northern hemisphere, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., ėds., Quaternary Glaciations in the Northern Hemisphere: Quaternary Science Reviews, Volume 5, pp. 509-510.

Grey, M., 1985, The Quaternary ice age: Cambridge University Press, Cambridge.

Lowe, J.J. and Walker, M.J.C., 1984, Reconstructing quaternary environments: Longman, Lon don.

Merrill, R.K. and Péwé, T.L., 1977, Late Cenozoic geology of the White Mountains: Arizona Bureau of Geology and Mineral Technology, Special Paper no. 1.

Péwé, T.L., Merrill, R.K. and Updike R.G., 1984, Glaciation in the San Francisco Peaks and the White Mountains, *in* Smiley, T. L. et al, Landscapes of Arizona -- The Geological Story, pp. 327-357.

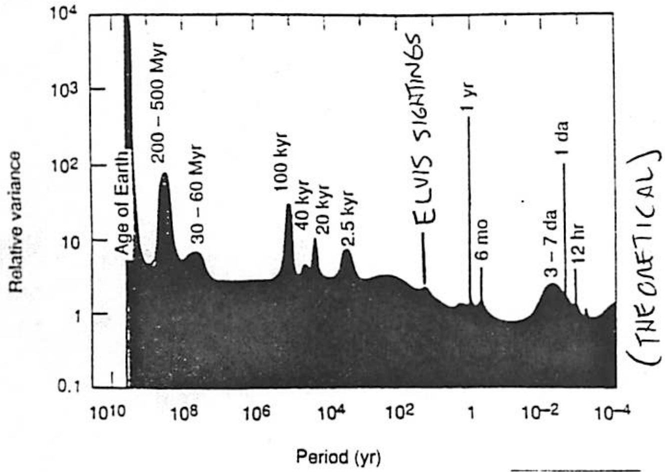
Richmond, G.M., 1986, Stratigraphy and correlation of glacial deposits of the Rocky Mountains, the Colorado Plateau and the ranges of the Great Basin, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., eds., Quaternary Glaciations in the Northern Hemisphere: Quaternary Science Reviews, Volume 5, pp. 99-127.

Richmond, G.M. and Fullerton, D.S., 1986, Introduction to Quaternary glaciations in the United States of America, *in* Sibrava, V., Bowen, D.Q., and Richmond, G.M., eds., Quaternary Glaciations in the Northern Hemisphere: Quaternary Science Reviews, Volume 5, pp. 3-10.

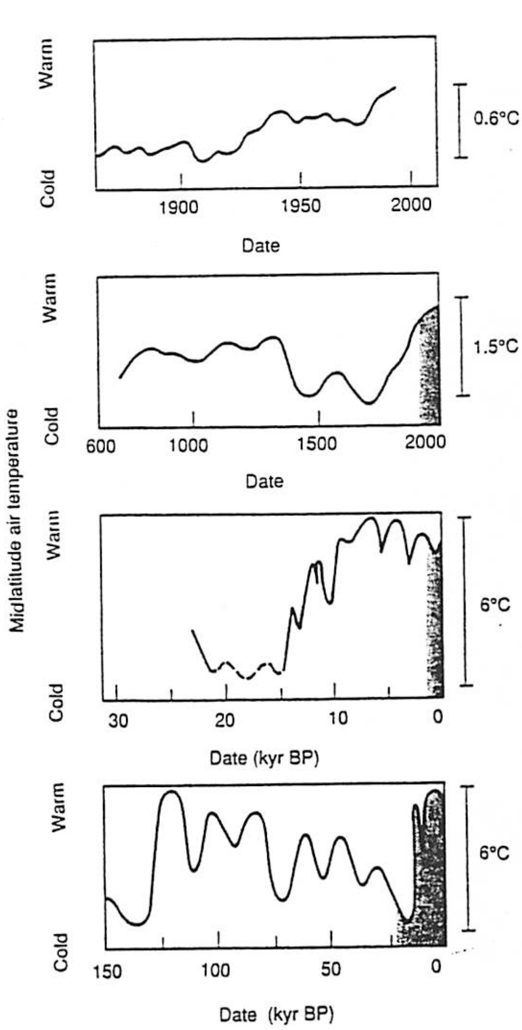
*********GLOBAL CLIMATE CYCLES*********

by The King
(as told to David Trilling)

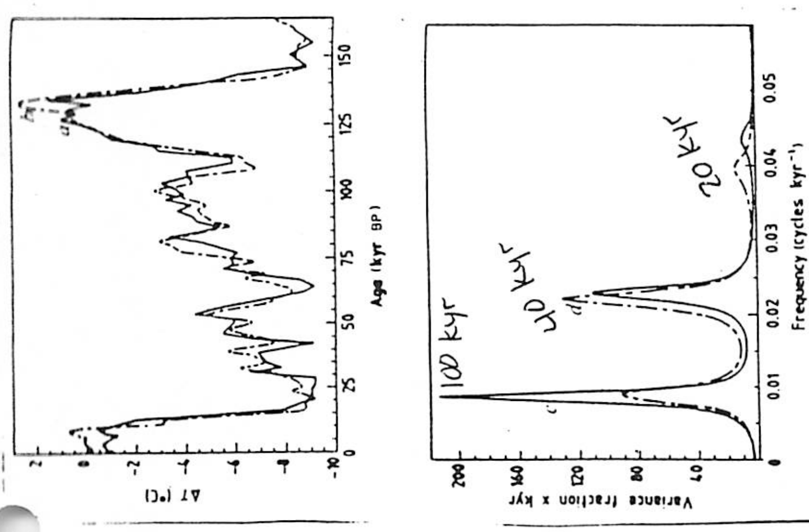
Global climate cycling has been recorded with various time resolutions as far back as 160 000 years, and predicted for ages much greater than this. There are climate cycles with periods approximately 23 000, 45 000, and 100 000 years due to orbital variations. Earth's orbital parameters seem to vary regularly and periodically; Mars' obliquity is chaotic, though, possibly implying episodes of drastically different climates. The current temperature increase on Earth, largely suspected to be due to anthropogenic emissions of greenhouse gasses, primarily CO_2, is estimated to be far less than some fanatics would claim (Michael Burns, for instance).



Relative Variance of Periodic Climate Cycles
(Graedel and Crutzen, 1993)



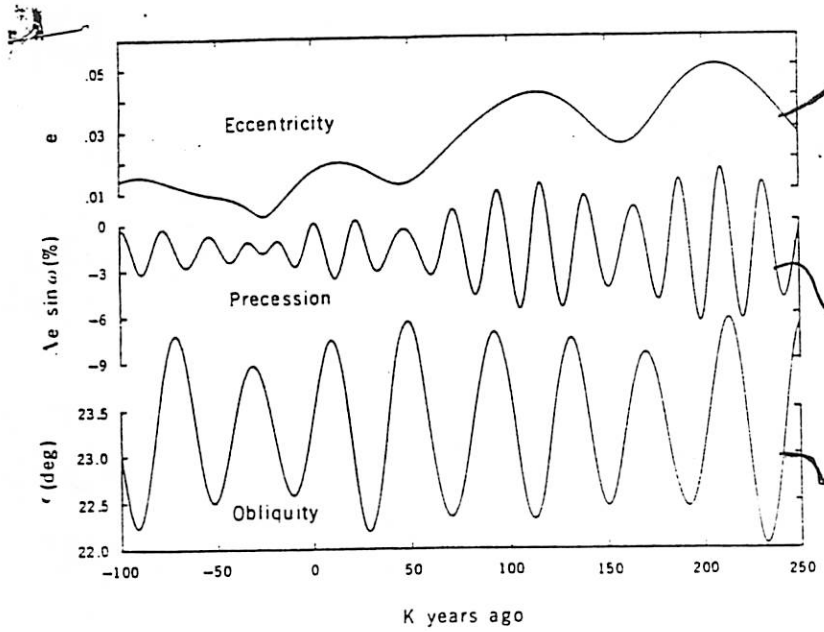
General Temperature Trends on Various Time Scales (Graedel and Crutzen, 1993)



Temp. vs. Age and Variance vs. Frequency (1/time)

Data: Vostok (Antarctica) Ice Core.
(Genthon et al., 1987).

Variations in Earth's Orbital Geometry with Time (Imbrie and Imbrie, 1980)
(affects solar energy influx, precession of solstices w.r.t. perihelion, etc.)



Pd ~ 100,000 YEARS.

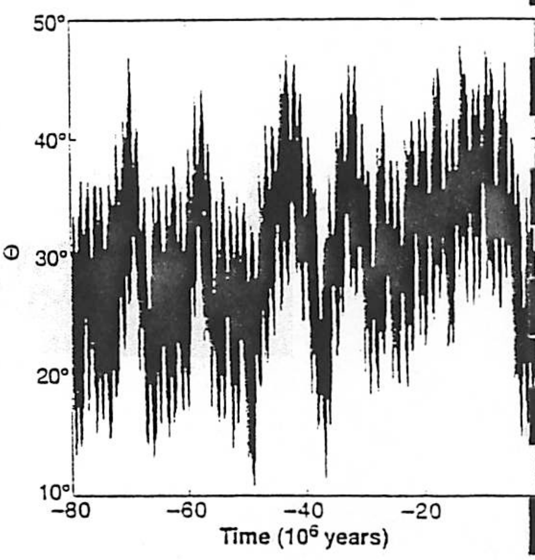
ELVIS GOT MORE ECCENTRIC WITH TIME!

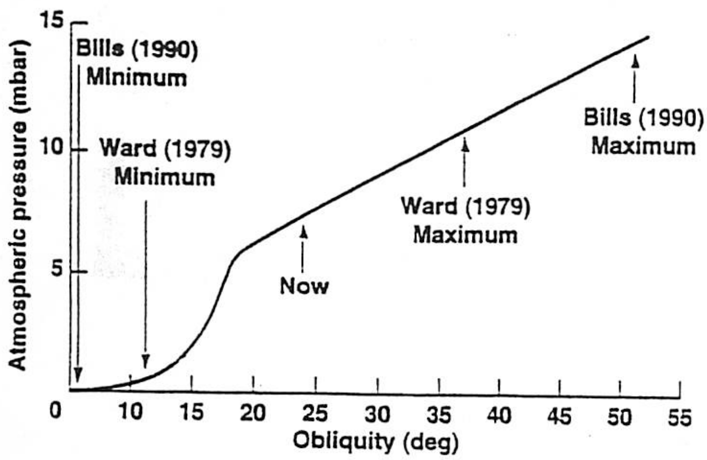
Pd ~ 23,000 YEARS

Pd ~ 40,000 YRS.

Obliquity of Mars versus time. Chaotic! (Touma and Wisdom, 1993). Implications for surface temperature and radically different climates.

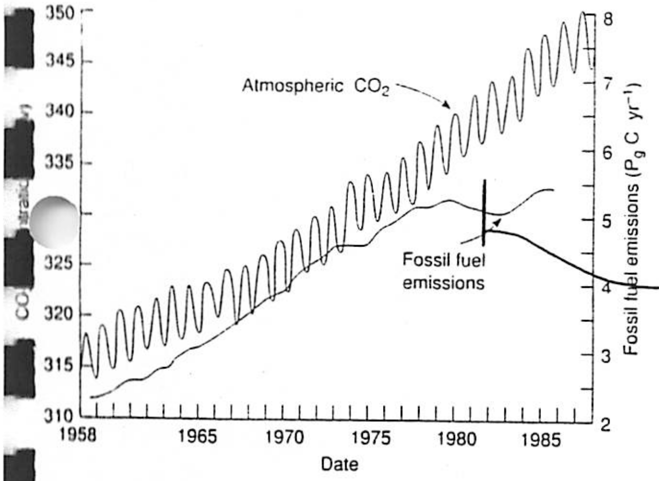
(ALSO THE MOTIONS OF ELVIS' HIPS ON THE ED SULLIVAN SHOW) →





ELVIS' WEIGHT THROUGH TIME? EVER INCREASING....

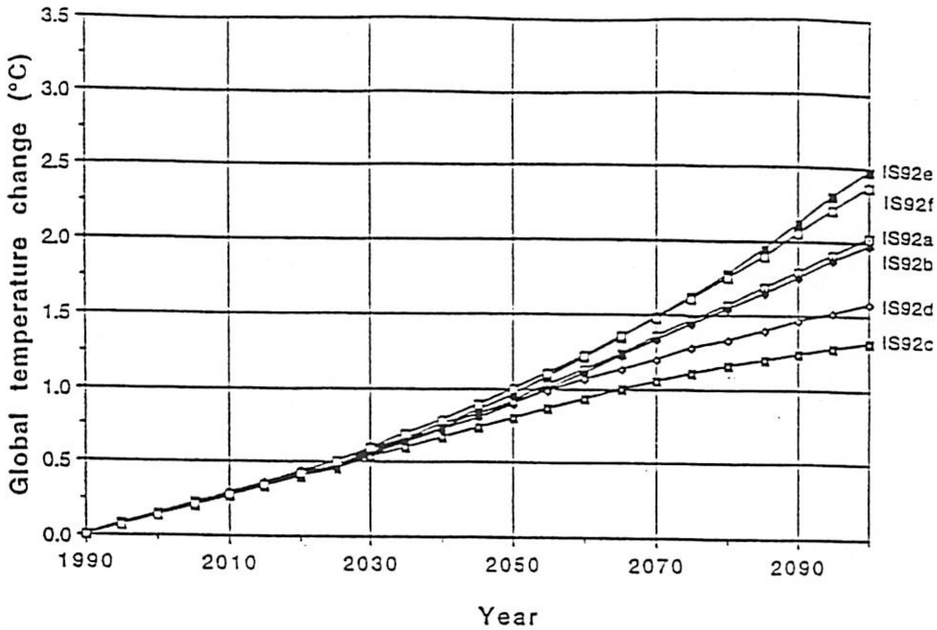
Atmospheric Pressure on Mars versus Obliquity (Kieffer and Zent, in *MARS*). Different climates at substantially different obliquities?



CO_2 versus time – anthropogenic emissions and effects
Causing global warming?

(Graedel and Crutzen, 1993).

NOTICE DECREASE IN FOSSIL FUEL EMISSIONS 1 YEAR AFTER ELVIS' DEATH, WHEN THE MEMORIAL FLAMES WERE EXTINGUISHED.



(Predicted) Global Temperature Change versus time (Intergovernmental Panel on Climate Change, 1995).

Gaia Madness:

A Touchy-Feely New-Agey Crystal-Wearing Bizarre Idea that The Earth -- GAIA – is a Living Organism, and as such "heals" herself of "environmental" diseases -- like too much CO_2, the aftermath of the K/T impactor, or even overpopulation. See James Lovelock ("Creator of the Gaia Theory")'s *HEALING GAIA: Practical Medicine for the Planet* for a good laugh and fluffy quasi-scientifoid treatment of this topic.

Lovelock essentially takes the idea of feedback mechanisms and assigns a mystical 'consciousness' to them, implying that Gaia acts in a willful manner to heal her environmental problems.

As if.

"ALL ENVIRONMENTAL PROBLEMS ULTIMATELY DERIVE FROM AN ABSENCE OF ELVIS" JAMES LOVELOCK, UPON SEEING THE LIGHT.

Glaciers and Glaciation - Earth and Beyond Ralph Lorenz

What is a glacier?

The conventional definition of 'a river of ice' is somewhat restrictive. A gravity-driven flow would include landslides, katabatic winds, lava flows and rivers, as well as glaciers. Perhaps a working definition might be 'a slow gravity-driven flow of a solid material precipitated onto the surface'. This neatly eliminates, albeit fudgingly, the above counterexamples.

Glaciers on Earth

Conventional ice glaciers are covered elsewhere in this handout. It should be noted, however, for the purpose of comparison, that ice moves in two ways - by viscous deformation, and by sliding on a basal layer of meltwater and debris. The latter mode gives much faster rates of movement and erosion.

Rock Glaciers

These are simply glaciers composed mostly of rocks, bound together by an ice matrix. They differ from conventional glaciers only in their rock fraction, which leads to much slower creep rates.

Salt Glaciers

These also have the name 'namakier' (derived from the Farsi 'namak'='salt') These glaciers, known to the West since 1927 (Lees, 1927) are the surface manifestation of salt diapirs which have welled up through the surrounding rock, and whose rock caps have been eroded away, allowing the halite dome to emerge onto the surface. The salt was deposited when the Sea of Tethys dried up (it stretches, but is compliant with, our definition above, in that the salt must have precipitated out... I include these because they are interesting) and the geology of the area has been studied in some detail - the salt domes form impermeable reservoirs for hydrocarbons, of obvious economic interest.

Just as glacier flow on Earth is driven by the budget of supply by precipitation against loss by ice flow, melting and sublimation, a salt budget can be derived balancing loss by solution in rainwater against delivery from below (Talbot and Jarvis, 1984). Of note is that the effective viscosity of halite is strongly dependent upon its water content, and thus namakier flow is strongly episodic, with rapid (0.5 m/day) advances following rains. The thickness of the closely-studied namakier ('Kuh-e-Namak (Dashti)' Talbot and Jarvis, 1984) is modest - 50-100m, and the average rate of flow is small - less than a meter a year. Using typical erosion rate estimates, e.g. $E = DT\ ec\ U^{ev}$, with DT= the age of the deposit (~10^5 yr), ec~10^{-4}, ev~1 (Harbor, 1992) and U the sliding velocity, suggests no more than a few metres of erosion should have taken place during the ~10^5 year age of the deposit. Talbot (personal communication, 1996) reports he has never observed evidence of erosional or depositional features associated with salt glaciers, however.

Glaciers on Mars...

The mental connection between Mars and glaciation is an easy one - Mar's most prominent telescopic features are its polar caps. However, polar caps do not necessarily imply glaciers - present surface temperatures are such that CO_2 and H_2O have high viscosities (see PTYS 505b Homework 1)such that flow transport is small compared with the sublimation fluxes. Note that the present-day poles at least have differing compositions (due to the combined obliquity and eccentricity of Mars' orbit), with the residual south pole composed mostly of CO_2.

At the end of (or in cool episodes in) the 'Warm, Wet Early Mars', water ice deposits may have been widespread. The abstract of Kargel and Strom's (1992) paper says it all : 'A large number of anomalous landforms on Mars can be attributed to glaciation...'. Indeed. They can also be attributed to other processes, however. To an unbeliever, the photographic evidence they present is far from totally convincing.

Triton

Triton presents an interesting case - it has polar caps of nitrogen ice. The rheology of this material has been estimated by Elusciewicz and Stevenson (1990).

The considerable obliquity leads to large variations in insolation, such that on decade timescales large thicknesses of ice can build up. However, internal heating limits the thickness of such deposits by basal melting (Brown and Kirk, 1994). The caps are therefore limited in extent by the flow of ice to warmer lower latitudes where it re-sublimes.

Titan

Titan possibly has all kinds of organic sludge all over it. Surface temperatures, in part due to a methane and hydrogen greenhouse effect, are too high to permit methane ice on the surface. However, if the methane supply (from a surface or subsurface reservoir) ever fell below the level required to balance the continuous depletion by photolysis, the greenhouse effect disappears, and temperatures could fall to levels where the nitrogen atmosphere could condense out, perhaps as a solid (work in preparation).

Mad Speculations about other solar systems

In our own solar system, only two planets have glaciers in the sense of gravity-driven flows of solids in a cycle completed by atmospheric transport: Triton and Earth. The salt glaciers on Earth (not really cyclic) and sulphur (not solid) and SO_2 (not enough of it to flow, as far as we know) on Io don't really fit the bill.

There is a common thread linking the glacial cases - the glacial material must have a sufficiently high precipitation flux that it forces the surface deposit to move. The implications are that the material must be fairly abundant, and temperature variations over the surface are sufficient to require significant transport of latent heat. Temperatures must be such that vapour pressures are adequate to allow reasonable vapour fluxes at the deposition site, but not so high that it resublimates before it can flow: an implication is that surface temperatures must be close to the freezing point, where the vapour pressure curve is steep: here the viscosity of the solid is at its lowest too. Thus the presence of glaciers requires a solution of the 'goldilocks problem' - similar to that of defining habitable regions around stars.

The possibility of glaciers is a little easier, in that we are not restricted to liquid water, but have a choice of volatiles, such as SO_2, NH_3, CO_2, H_2O, CH_4, CO, N_2. It might be interesting to define, using vapour pressure and/or rheology information, 'glacial zones' for solar systems for each of these materials.

Glaciations on Fictional Earths

Just for fun, why confine ourselves to the real universe? The effects of even modest climate change only a few centuries ago were profound on a human level - large areas of Scotland became agriculturally unviable during the little Ice Age, and climate change may have led to the desertion of Nova Scotia and Greenland by the Vikings. The effects of glaciation seen by late-20th century individuals is explored in a number of science fiction stories : John Gribbin's 'The Seventh Winter' is gripping, and was written in the late 70's, when the scientific consensus was that the Earth was cooling (Gribbin is a prolific science journalist). A more recent story, 'Ragnarok', involves a jaded scientist attempting to detonate a nuclear device in the mid-atlantic ridge: the steam explosion resulting from the water/magma mixing would induce a nuclear winter: among the beneficiaries would be the Libyans, whose arid wastes would become fertile, this providing the motivation for them to provide the nuclear device.. Jerry Pournelle's 'Fallen Angels' is a rather implausible and evangelistically-pro-science story set on an Earth where the Green lobby has taken over and technology is outlawed. Lots of trees have removed CO_2 from the atmosphere, and glaciation has begun. The encroachment of the ice sheet over the northern USA is graphically described.

A little off-topic, Robert Forward's 'Rocheworld' describes a planetary system around Barnard's Star, complete with a near-contact binary planet. Gravity-driven flows of different ammonia-water phases, some of which threaten the humans exploring the system, are described in detail. The book comes complete with a phase diagram in an appendix.... truly a book for planetologists.

References

C J Talbot and R J Jarvis 1984. Age, Budget and Dynamics of an Active Salt Extrusion in Iran. Journal of Structural Geology, vol.6 pp521-533

J M Harbor 1992. Numerical Modeliing of the Development of U-shaped valleys by Glacial Erosion, Geological Society of America Bulletin, vol.104 pp.1364-1375

J S Kargel and R G Strom 1992. Ancient Glaciation on Mars, Geology, vol.20 pp.3-7

G M Lees 1927. Saltglescher in Persien, Mitt. Geol Ges. Wien, vol.22 29-34

Eluskiewicz and D J Stevenson 1990 Rheology of Solid Methane and Nitrogen: Application to Triton Geophysical Research Letters vol.17 pp.1753-1756

R H Brown and R L Kirk 1994 Coupling of Volatile Heat Transport and Internal Heat Flow on Triton, JGR vol.99 1965-1981

Talbot & Jarvis 1984

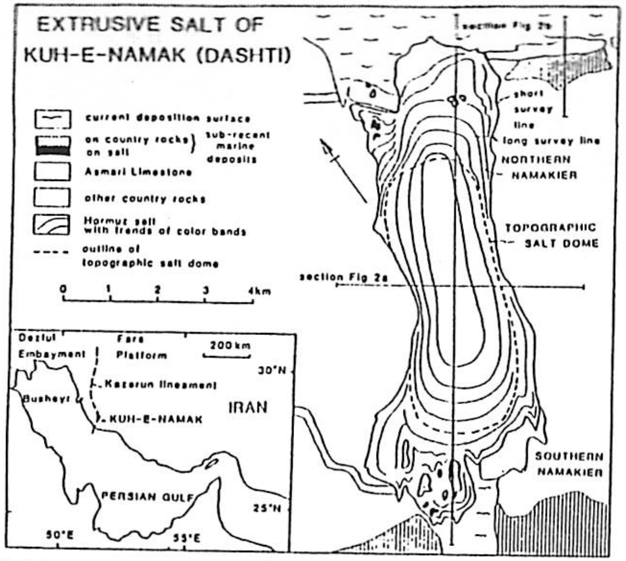


Fig. 1. Geological sketch map of the salt extrusives at Kuh-e-Namak (Dashti) showing locations of profiles in Fig. 2.

r to move l-

(46)

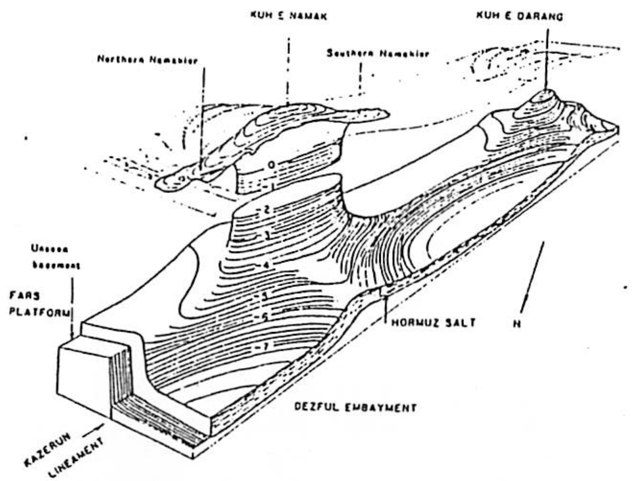


Fig. 3. Three-dimensional sketch of the salt bodies at Kuh-e-Namak and Kuh-e-Darang rising from the same salt pillow which developed at the southern end of the Kazerun lineament in Jurassic times. The recent surface mentioned in the caption to Fig. 2(b) and text can be seen to define an anticline through the rift across Kuh-e-Darang and a syncline between Kuh-e-Namak and Kuh-e-Darang.

Kargel & Strom 1992

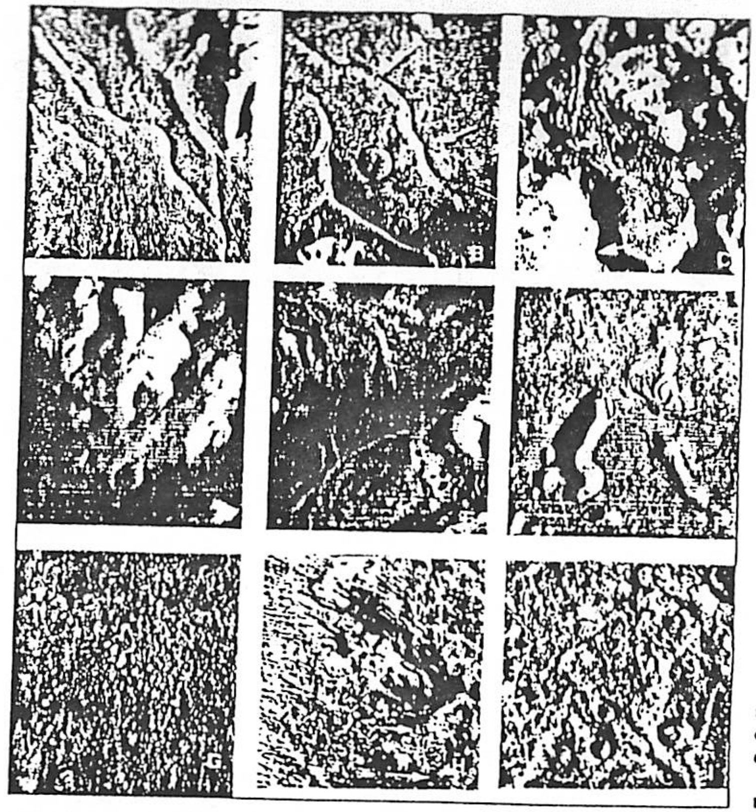


Figure 2. A: Anastomosing section of Argyre's sinuous ridges partially overridden by lobate debris apron and overlapped by smooth plains. Scene width ~50 km. Viking Orbiter 567B30. B: Argyre sinuous ridge system showing locally double-ridged, rounded, and sharp-crested sections. Mountain in lower left has alluvial fan-like deposit possibly caused by meltwater. Small pitted dome (arrow) may be a pingo. Note smooth plains burying craters. Scene width ~50 km. Viking Orbiter 567B33. C: Argyre's Charitum Montes may be heavily modified by glaciation. Sharp-crested semicircular mountain ridge (arrow) may be crater modified into cirque, from which outwash appears to emanate. Scene width ~120 km. Viking Orbiter 352S24. D: Lobate debris aprons (rock glaciers) issue from possible cirques and arêtes in Charitum Montes. Scene width ~50 km. Viking Orbiter 567B09. E: Braided fluvial erosional and/or depositional deposit in Argyre. Scene width ~40 km. Viking Orbiter 567B15. F: Complex terrain on floor of Argyre possibly formed by massive ice disintegration, glaciolacustrine deposition, and cliff erosion by wave action. Scene width ~35 km. Viking Orbiter 568B49. G: Pitted terrain on floor of Argyre interpreted as kettled plains. Scene width ~40 km. Viking Orbiter 568B12. H. Sculptured floor of Argyre (left and bottom), probably eroded by ice and/or meltwater. Arrows indicate segmented esker (lower right). Debris blanket (right), probably ejecta of crater Galle, partially buries sculptured hills and esker, but subsequently was scoured or collapsed, thereby forming finger-lake-sized depressions (top right). Scene width ~200 km. I: Cratered uplands east of Argyre, showing part of quasi-dendritic esker (top left arrow) and tunnel valley system (lower right arrow), traceable to braided complex in E. Paleoflow was to lower right.

It is possible that evidence for glaciation may be more compelling in the original images, but judge for yourself.

Why Are We Here and not Somewhere Else?

And How Long Have we Got?

PLEASE NOTE!

→ [the ramblings of a non-planetary scientist-type person] ←

Robert F. Coker

I. What's so Special about Earth?

Obviously we're nicely adapted to Earth's environment. But couldn't have life evolved on Mars or Venus? If by life we mean something rather like us, the answer seems to be no. So what's so special about Sol 3? After some thought, four things come to mind: 1) Earth has (and has had for quite some time) water oceans, 2) Earth has a strong intrinsic magnetic field, 3) Earth is slightly more massive than either Mars or Venus, and 4) Earth has a decent sized moon. In terms of life, the first difference seems the most important (and seems to be related to the other three). So, tentatively, let's say Earth is special because it has water oceans.

II. Why are we the only ones with Surface Water Oceans?

There's certainly a lot of H_2O around but not much in the form of liquid. How is it that the Earth is just the right temperature to have most of its H_2O in liquid form? If we were just a little closer to the sun, bad things would happen. Water would vaporize and disassociate; then the hydrogen would go bye-bye. Then the carbonate-silicate cycle would get impaired and pesky CO_2 would make things even hotter. If we were just a little further from the sun, water would freeze and plate action would slow down or even stop. CO_2 might help prevent freezing via the ol' greenhouse effect, but if it's cold enough to form CO_2 clouds, the increased albedo would push Earth into runaway glaciation.

III. What are the Limits on our Location?

The so-called Habitable Zone (HZ) for an Earth-sized planet around the sun is, at the moment, between .95 to 1.37 A.U. But 4 Gyr ago, the sun only had 70% of today's luminosity so planets at the outer edge of the present HZ would have been frozen. This squeezes the HZ to between 0.95 and 1.16 A.U. Not much room for error. In fact, to be a truly peachy world, a planet needs to never get outside the HZ. So no highly eccentric or chaotic orbits are allowed (a Mars-like orbit wouldn't cut it).

IV. So Why is the Earth so Well-Behaved?

Not only do we not have annoying nearby massive planets to tweak our orbit, but we do have the Moon which, interestingly enough, actually stabilizes our orbit. Without Luna , every 1 Myr or so the Earth would get a large enough eccentricity to wander too close to the sun and our oceans would start leaking away. The Earth would also have a more variable obliquity (15-35 degrees over 15 Myr) and a larger variance in mean daily insulation ($\pm$ 20% more). Life likes to have more stability than that....

V. Is the Earth itself Special?

Our location and neighbors seem perfect. Is the Earth itself critical to our existence? The Earth is more massive than Venus or Mars, allowing for more atmosphere retention and longer tectonic activity. Both of these widen the HZ in both time and space. If the Earth were much larger, water retention at the inner edge of the HZ would be easier but heat retention at the outer edge would be more difficult. The Moon would also have to be correspondingly bigger. Another Terran pecularity is our strong magnetic field. Does water (which may be crucial to plate tectonics and thus the motions of the core) indirectly strengthen our magnetosphere? Certainly without our protective magnetosphere, pre-biotic material wouldn't have been able to form more complex molecules before getting zapped by energetic solar particles.

VI. So how long will this Delicate Balance last?

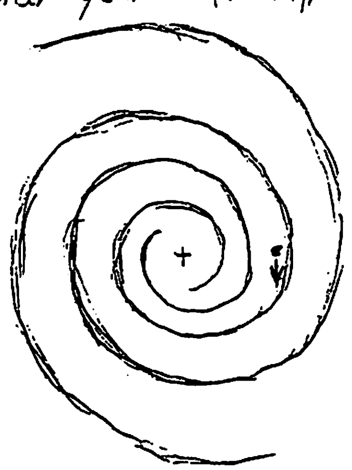
If the Earth were different in just about any way (location, mass, density, orbital parameters, the moon, compositon, etc.) in any large (or even not-so-large) amount, life as we know it wouldn't be around. Although it's not clear how robust the Earth's climate is to cars, it's clearly rather fragile on larger scales. In fact, excluding the human factor (and impacts), how long will life as we know it be possible on Earth? The lifetime of the sun, right? Not quite. First, there are influences external to the solar system. Although no supernova candidate (barring a lot of strange obelisks) is near enough to threaten us, there is the matter of interstellar matter. In the next few Myr or so, the sun will be entering a spiral arm where the ISM is more dense than our IPM. Will this be our doom? Roughly 0.5 magnitudes of visual extinction between us and the sun would leave the Earth too cold to support water oceans. Would a jump in IPM density of a few orders of magnitude and a larger prevalance of micron-size grains be sufficient? Probably not.

So this leaves us with the sun as our grim reaper. But sooner than might be expected. 4 Gyr ago, the Earth was almost too cold but in about 1 Gyr the sun will be 10% more luminous than it is today. This is just enough to cause water to trickle out of our atmosphere. So we have just 1 Gyr to find another world as perfectly balanced between ice and steam as the Earth. Luckily, it appears that in F, G, and K star systems, if terrastrial planets are present, one is likely to form in the HZ. Present estimates say the odds are good that a lovely potential colony world is less than 50 light years away......

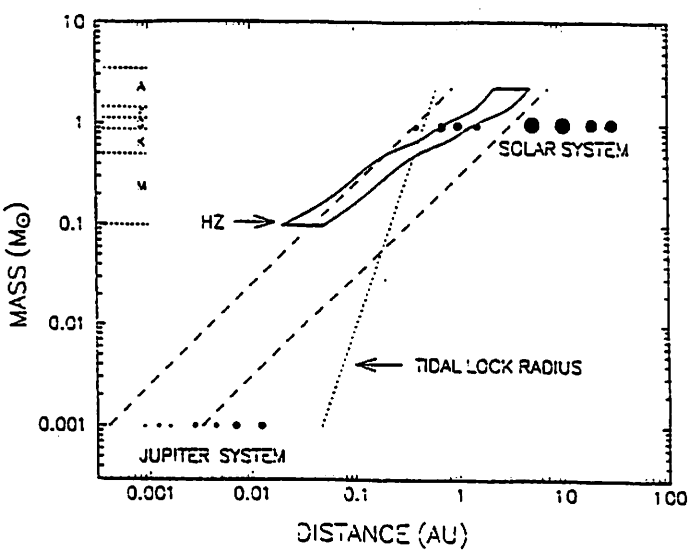
VII. Bibliography

Laskar, J., *et al.*, 1993, *Astr. Ap.*, **270**, 522.
Li, Z., *et al.*, 1991, *Ap. J.*, **378**, 93.
Sackmann, I, *et al.*, 1993, *Ap. J.*, **418**, 457.
Kasting, J., *et al.*, 1993, *Icarus*, **101**, 108.

"solar year" ≃ 240 Myr



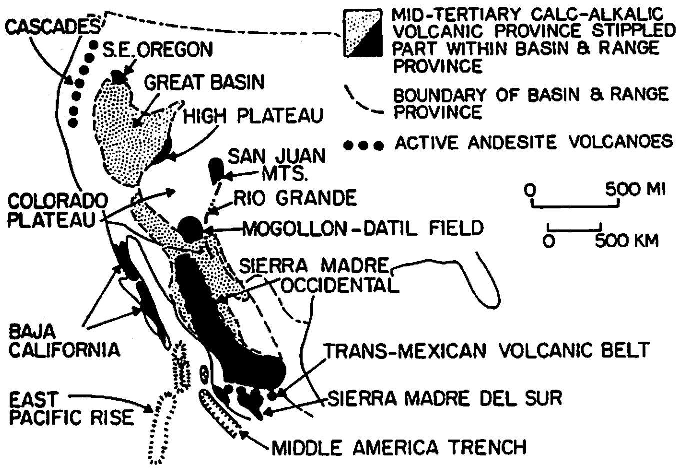
R = 8.5 kpc
V = 220 km/sec

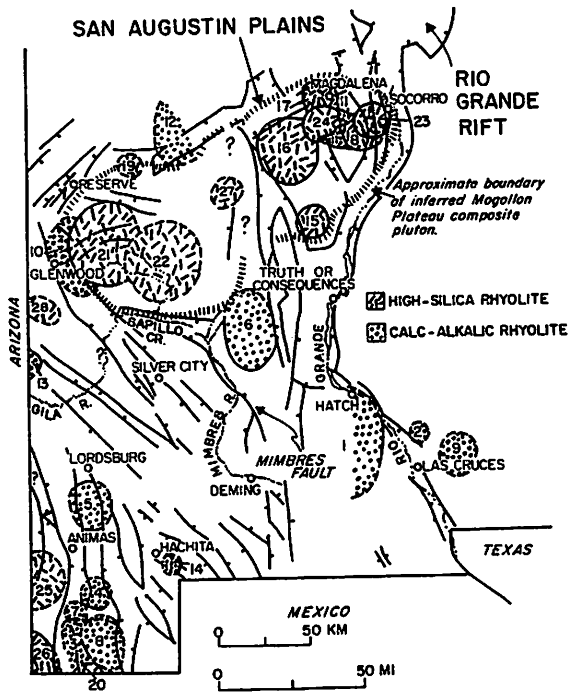


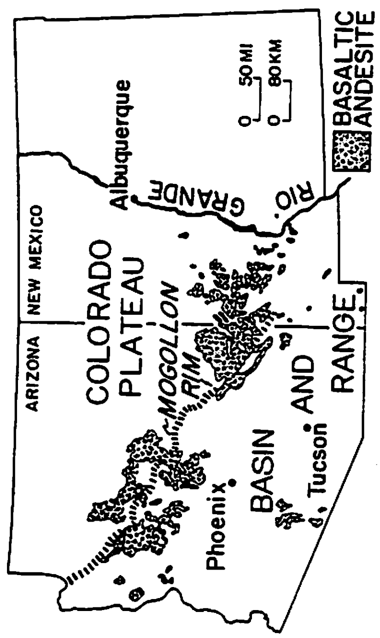
Colorado Plateau Rim Volcanism

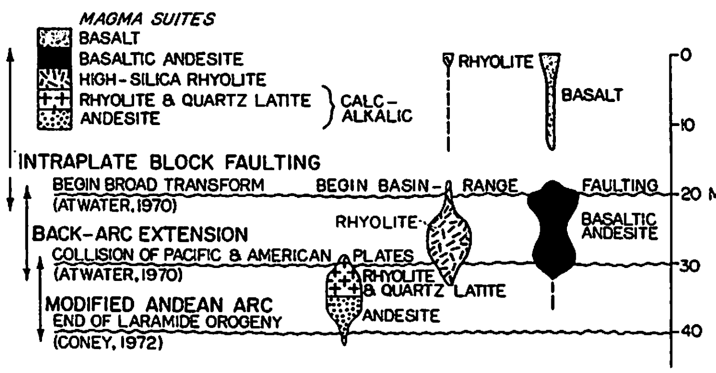
with your Hostess with Neuroses ➼ *Jennifer Grier*

Page 1: Potentially Useless Figures; Page 2: Hopefully Relevant Map of AZ and NM.



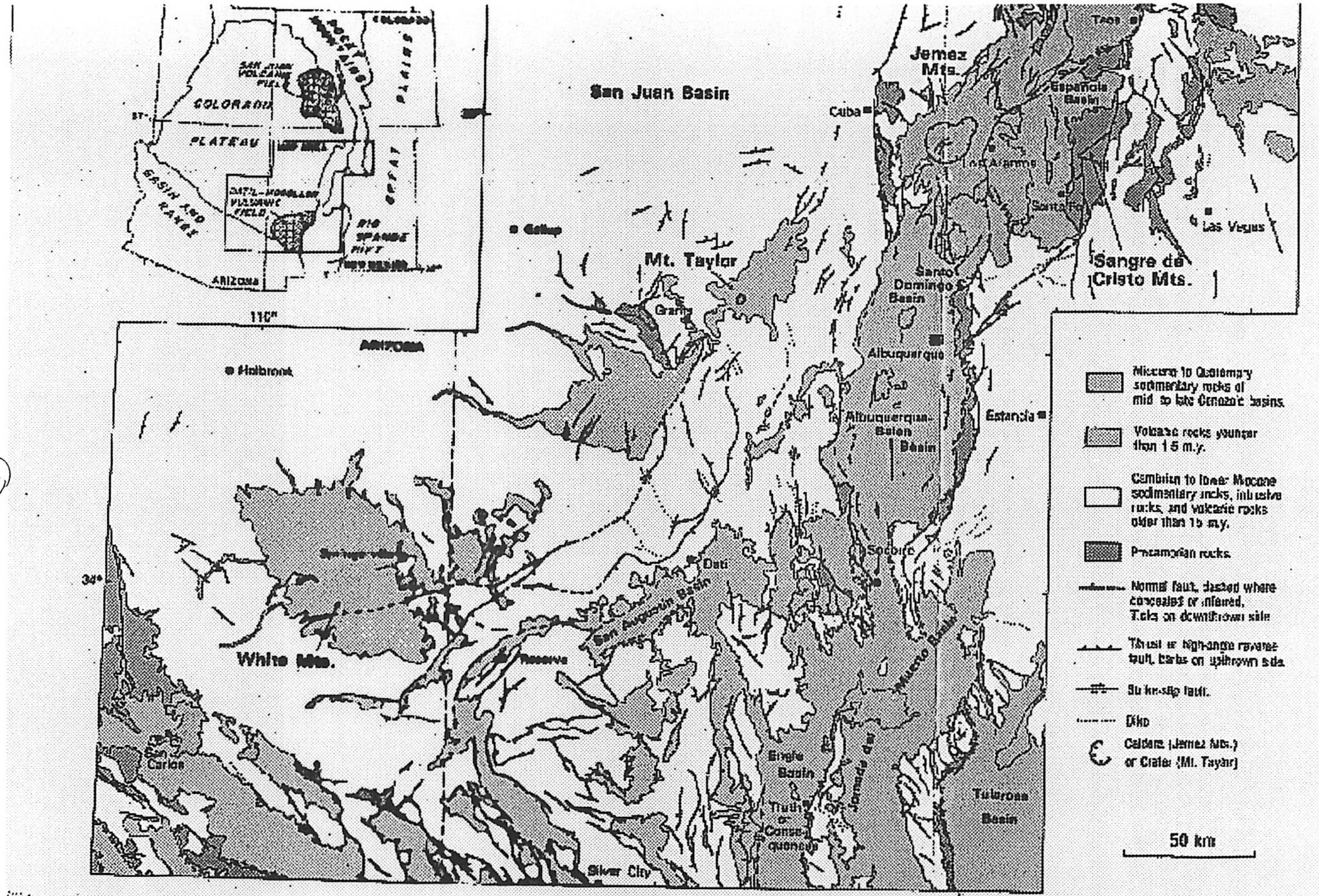






Captions for Potentially Useless Figures Fig 1: Mid-Tertiary volcanic province of southwestern North America. Fig 2: Provisional tectonic sketch map of southwestern New Mexico. Numbered circles outline the inner walls of mid-tertiary ash-flow tuff cauldrons. Fig 3: Correlation of volcanic suites with tectonic events at the western margin of the American plate. Fig 4: Distribution of Oligocene to Miocene basaltic andesite and associated rocks, AZ and NM.

Refs: Rio Grand Rift, Tectonics and Magmatism. ed Riecker R.E., 1979, AGU, LithoCrafters, Inc., Michigan. Elston W.E., and Bornhorst T.J., The Rio Grande Rift in Context of Regional Post-40 MY Volcanic and Tectonic Events. Baldridge, Bartov and Kron, Geologic Map of the Rio Grande Rift and Southeastern Colorado Plateau.



TECTONIC MAP

COLORADO PLATEAU: UPLIFT MECHANISM(S)

by Jim Head (West)

The Colorado Plateau is the second highest plateau on earth. It has receive a great deal of scientific attention, most recently being the sole topic of two sessions at the Fall AGU meeting. Arriving at a plausible mechanism for uplifting a large section of the crust to an elevation of two kilometers has been a fruitful, if somewhat contradictory area of study the last 25 years. This is one of those problems that has been solved more than once in mutually exclusive ways.

The plateau has a nearly uniform elevation of 2 km and has apparently behaved as a coherent unit throughout the Cenozoic. It is bounded by the Rio Grande Rift to the east and the Basin and Range Province to the west and southwest (Figure 1). Volcanism and tectonism is largely confined to the margins of the plateau. Gravity data indicates that the plateau is in isostatic equilibrium. Further data are more controversial. The interior of the plateau is thought to be in a compressive stress state (Thompson and Zoback 1979) or an extensive stress state (Jones 1995). The thickness of the crust is 40 kilometers (Black and Braile 1982, among others) or 50 kilometers (Beghoul and Barazangi 1989, Hauser and Lundy 1989). The corresponding compressional seismic wave velocity along the Moho (Pn) is 7.8km/sec or 8.1km/sec.

Hauser and Lundy: Colorado Plateau Moho at ~50 km

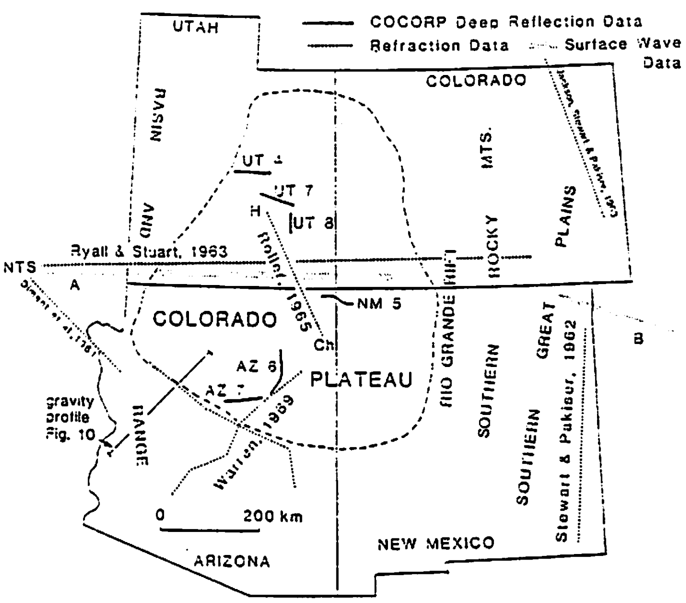


Fig. 1. Location map of COCORP deep reflection lines on the Colorado Plateau. The only reversed refraction profile on the Colorado Plateau [Roller, 1965] is between Hanksville (H), Utah, and Chinle (Ch), Arizona. Other refraction profiles of region are labeled with publication reference. A, surface wave profile [Keller et al., 1979a]; C, surface wave profile [Keller et al., 1979b].

Hauser and Lundy: Colorado Plateau Moho at ~50 km

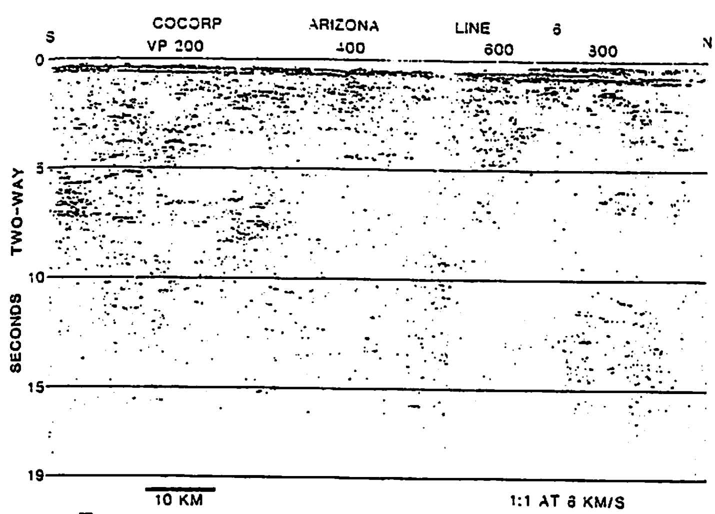


Fig. 2 COCORP line 6 from the Colorado Plateau north of Winslow; for location see Figure 1. Note the abundance of coherent reflections to about 16 s, below which there is a relative absence of reflections. Coherency filtered after stack for photographic enhancement. Time section in seconds two-way travel time. Datum at t=0 is 1600 m. Display scale is 1:1 at 6 km/s.

To sort some of that out, before COCORP (the Consortium for Continental Reflection Profiling) the depth to the Moho and Pn were thought to be 40km and 7.8km/sec respectively. This seismic velocity is somewhat low, indicating a warmer, less dense mantle beneath the plateau. About one kilometer of the uplift could be accounted for in this way. The rest would come from "underplating," addition of crustal material to the bottom of the crust. This has been known as the "thermal uplift model." By 1989, data from COCORP (e.g., Figure 2) indicated a crustal thickness of 50km and a Pn of 8.1km/sec. This seismic velocity is too high for a "warm" mantle. The new "delamination" model was posited (Beghoul and Barazangi). These two models are contrasted in Figure 3. The delamination model requires crustal thickening in addition to thermal expansion in the mantle. In this case, the thickening is ascribed to shear between the North American and Farallon plates. In each case, the uplift of the plateau is tied to the subduction of the Farallon plate about 30 million years ago. Keep in mind that in the Basin and Range Province, thermal uplift is invoked to explain the high heat flow, high elevation (1.5km), volcanism, and thin (25km) crust, while in the Colorado Plateau it has been invoked to explain the lower heat flow, high elevation, lack of volcanism, and a thick crust.

It would seem that this should have been all sorted out some time ago. A good deal of the controversy can be tied to determining Pn. Like all interpretations of seismic data, Pn is inverted from the bumps and wiggles of seismometers. Such inversions are not necessarily unique. In their 1989 paper advocating a Pn of 8.1km/sec, Hauser and Lundy take pains to re-analyze data back to Roller (1965). They claim the older data can be interpreted to support the high Pn, thicker crust model. In his 1995 abstract, Jones presents both interpretations, without coming down firmly in favor of one or the other. Unfortunately, I left AGU on Wednesday morning, and Jones' poster session was Thursday afternoon.

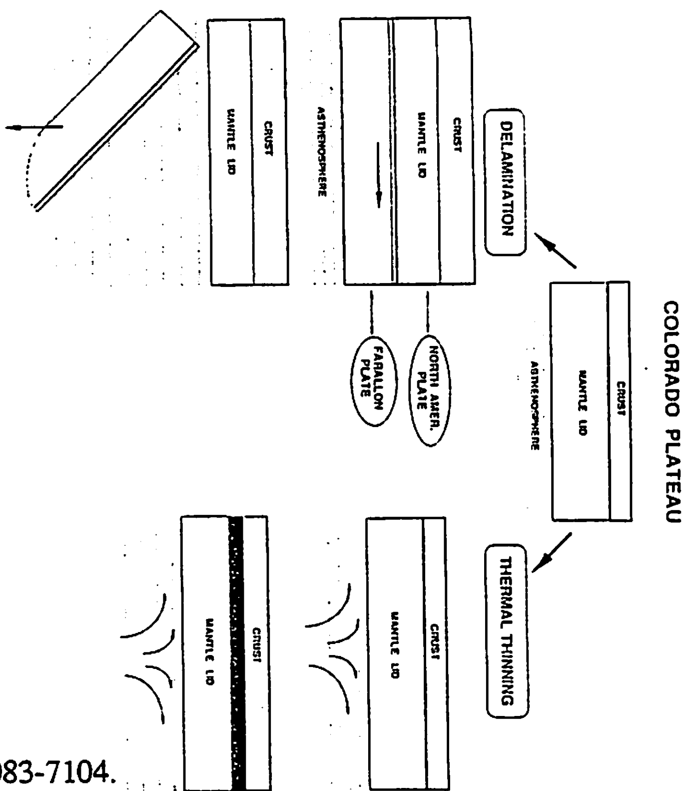


Fig. 3 This cartoon illustrates the main features of the most quoted models in the literature that explain the mechanism of uplift of the Colorado plateau. The left side represents the delamination model, and the right side represents the thermal thinning model. The delamination model is based on the hypothesis that the flat subducting Farallon slab in early Cenozoic time delaminated in mid-Cenozoic time from the overriding North American plate. The uplift is the result of thickening of the North American crust due to the shearing between the two plates [*Bird*, 1988] plus the thermal expansion of the hot asthenospheric material that replaced the relatively cold oceanic Farallon plate during the delamination event and the heating of the North American plate due to this hot asthenospheric material at its bottom. In the thermal thinning model a thermal perturbation started some time ago beneath the North American plate and thinned it from 130 to 70 km thick [*Morgan and Swanberg*, 1985, p. 49]. This thinning provides about 1 km of uplift; as the plateau is about 2 km high, the other 1 km is explained by possible crustal thickening due to magma injected in the lower crust (represented by a black bar in the lower right diagram).

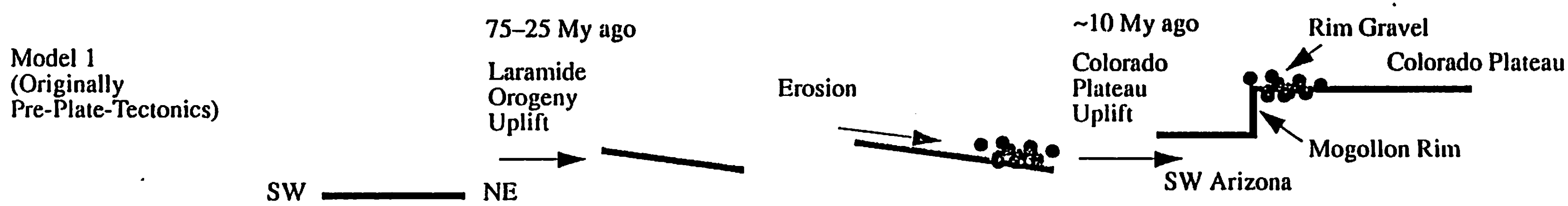
REFERENCES

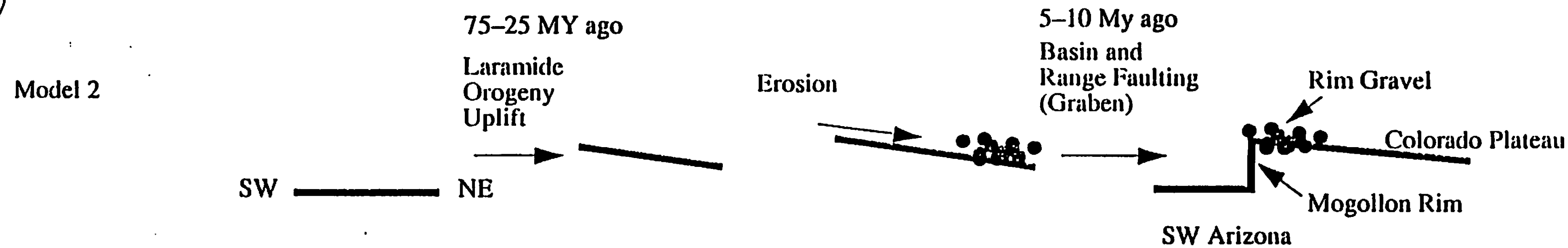
Beghoul and Barazangi (1989) JGR 94 7083-7104.
Black and Braile (1982) JGR 87 10,557-10568.
Hauser and Lundy (1989) JGR 94 7071-7081.
Thompson and Zoback (1979)
Roller (1965) Bull. Seismol. Soc. Am. 55 107-119.

Colorado Plateau Rim Gravels – M. Nolan 1992

Problem: Why is there gravel on top of the hill, which is from rocks older than the ones it sits on? All of the water flows from the North, now, but they're older than anything in that direction, and are more similar to the rocks far below. In fact, there's even bits of basalt otherwise found only to the South.

Answer: The hill used to go farther South, the gravel rolled downhill, then the old hill went away.





Issues remaining:

- Modern dating of some rim gravels yields 30-50 My.
- Stratigraphy is more complicated then pictured here.
- Perhaps an additional (pre- basin-and-range) faulting episode.
- Colorado River.
- Up to 80 km of scarp erosion.

Exposure: N. of Salt River Cyn on Rte 60.

54

The History, Geology, and Stratigraphy of the Salt River Canyon, Intrusive and Extrusive Volcanism on Earth, the Moon, Venus, and Mars, Spheroidal Weathering, and Their Effect on the Rise of the English Parliamentary System.

Bob "Hoppa" Reid and Nancy "Turtle" Chabot

Who needs color when you can have ***Gratuitous Use of FrameMaker™***

Salt River Canyon

General Setting

The Salt River lies just beyond the southwest margin of the Colorado Plateau. It has tributaries in the White Mountains, draining their southern and western edges. The river starts in the Transition Zone region of Arizona, and travels through the Transition Zone and Basin and Range provinces as it flows to the Gila River near Phoenix. (Figures 1 and 2)

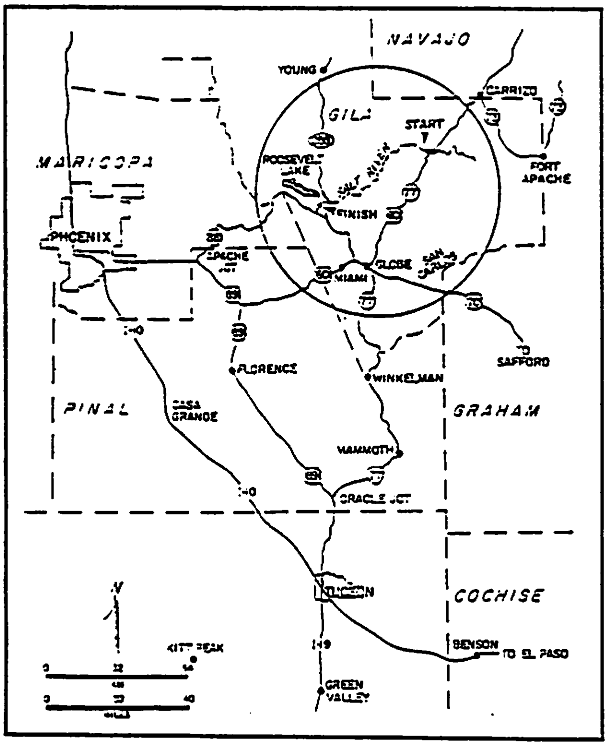


Figure 1 - Location map of Salt River Canyon region (from Davis, et al.)

The eastern end of the Salt River Canyon in the Transition Zone exhibits flat sedimentary strata and monoclinal folds characteristic of the Colorado Plateau region, and the western end of the Salt River Canyon in the Transition Zone exhibits tilted Tertiary volcanics and sediments bounded by normal faults, characteristic of the Basin and Range province.

The Salt River is currently used for recreation and is dammed in several places providing water, power, and flood control to

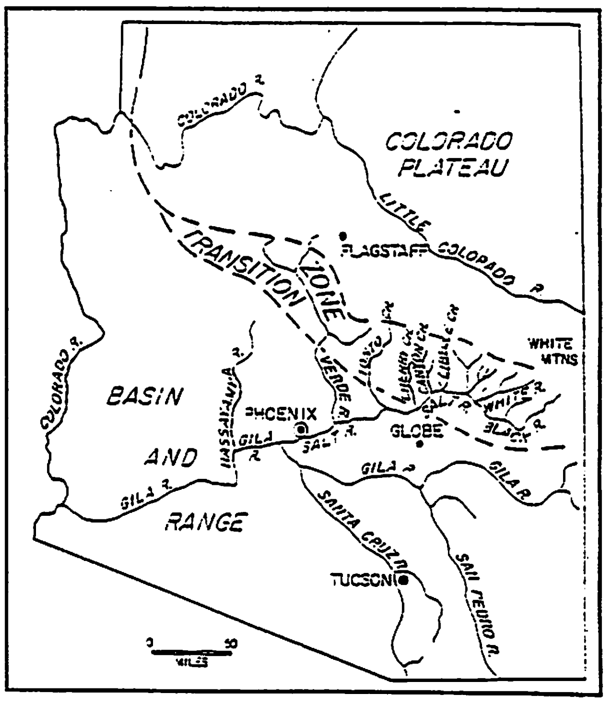


Figure 2 - Physiographic map of the Salt River Canyon region (from Davis, et al.)

central Arizona. The name "Salt River" has been used for centuries by the earliest natives in the region.

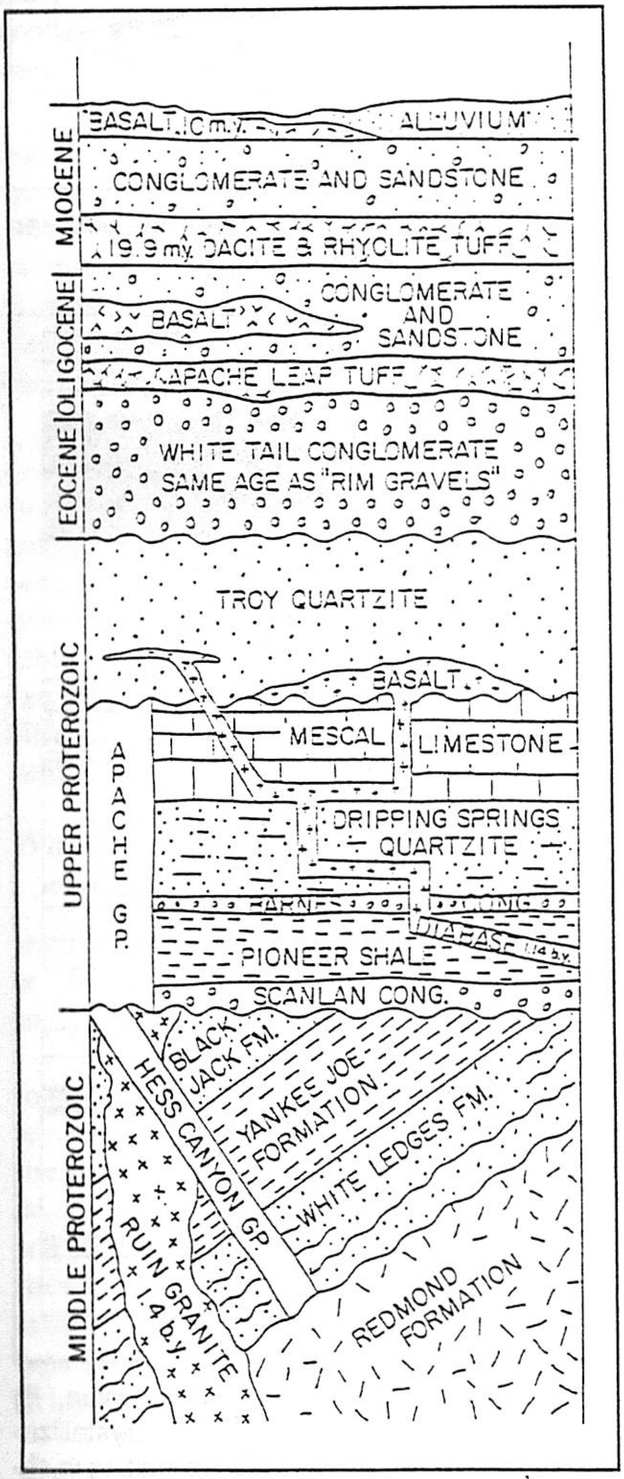


Figure 3 - Composite geologic column of the Salt River Canyon region (from Davis, et al.)

Geologic History

The geologic history of the Salt River Canyon region is varied and complex, and is summarized below. A geologic column is given in Figure 3.

- Basement rocks are Middle Proterozoic (1820-1420 m.y.a.) metavolcanic rocks overlain by metasedimentary rocks, intruded by granite batholiths, and tilted. These will not be seen in the canyon on our trip.

- The Apache Group consists of Upper Proterozoic (1420-1100 m.y.a.) conglomerate, siltstone to sandstone, and limestone, with some basalt flows near the top.

- Diabase intrusions (sill and dikes, see Intrusive vs. Extrusive Volcanism) fill the Apache Group, and to a lesser extent, the overlying Troy Quartzite. These intrusions have doubled the size of the ancient Apache Group.

- A period geologic quiescence follows (for 800-900 m.y.), then the whole region goes to hell in Paleozoic and Mesozoic time, but these rocks are not widely exposed at our viewing region of the canyon. There is marine deposition to the north and south, faulting and volcanism, subsequent erosion of Paleozoic rocks, deposition of Cretaceous strata. Then came Laramide tectonism, generation monoclines, deformation belts, and thrust faults, intrusion of granitic plutons, and tilting of Cretaceous strata.

- Back in to rocks we can easily see, layers of river sediments are interspersed with basalt flows and pyroclastics. The uppermost strata are river gravels and terrace deposits, stranded by the downcutting of the Salt River through the Transition Zone.

Intrusive vs. Extrusive Volcanism

The generalities of intrusive vs. extrusive volcanism are too extensive to go into, so we'll focus on the rocks we're going to see at the Salt River Canyon.

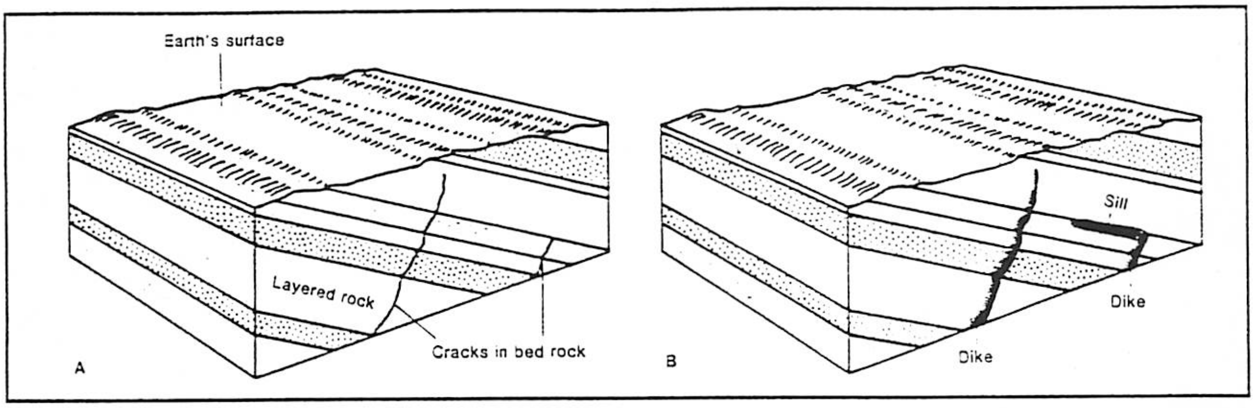


Figure 4 - A) Cracks of planes of weakness before intrusion of magma. B) Intrusions between layers are sills; intrusions across layers are dikes. (from Plummer and McGeary)

Intrusive Rocks

• **Granitic Batholiths:** The rocks of the Ruin Granite were intruded ~1.4 b.y.a. into the basement Precambrian rocks. These are not exposed at out viewing site.

• **Diabase Sills and Dikes:** These rocks were intruded into the Apache Group, doubling its size. Sills are coplanar with the surrounding strata, while dikes cut across the stratigraphy through cracks or faults. Sizes range from a few centimeters to hundreds of meters in width.

Extrusive Rocks

• **Basalt Flows:** Upper Proterozoic flow occur near the top of the Apache Group. Tertiary flows occur in the uppermost stratigraphy interspersed with river sediments and pyroclastics.

Identification

From this, we see that we have basalt flows interspersed with intrusions of diabase within the stratigraphy. How can we tell them apart?

1) **Stratigraphic Setting:** Intrusions can cut across strata, while basalt flows clearly must reside in a single stratigraphic layer. (Figure 4) That is, if a dike are observed to connect with parallel-lying layers, those layers can be interpreted as sill of intruded rock. Of course, you may happen across a feeder dike for the

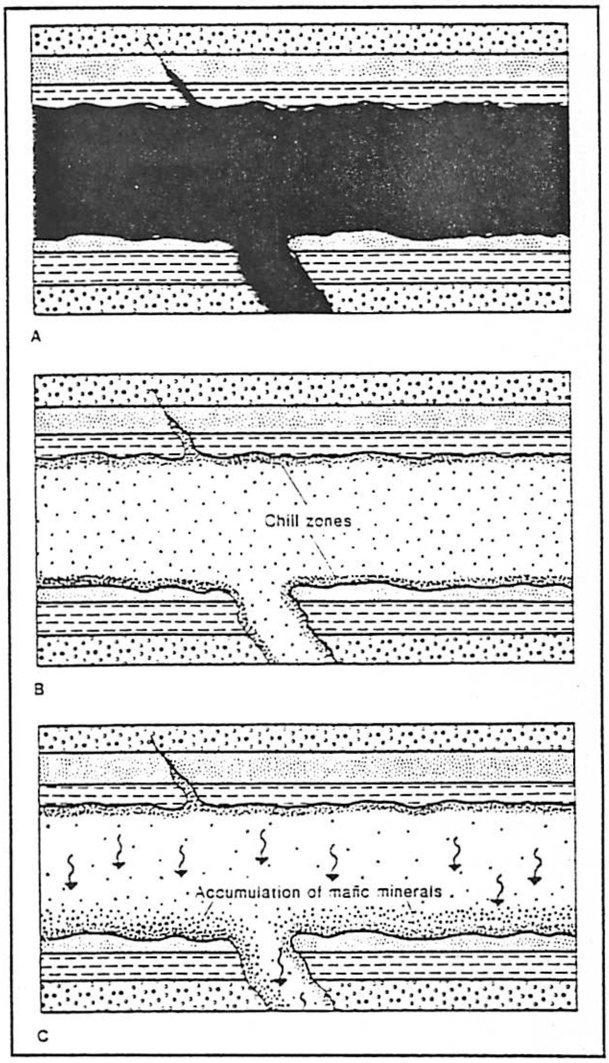


Figure 5 - A) Original magma intrusion. B) Slow cooling causes preferential crystallization. C) Crystals sink to bottom, resulting in differentiation of rock in intrusion. (from Plummer and McGeary)

basalt flow, which may lead to misinterpretation.

2) **Contact Metamorphism:** Intruded magma will alter rocks on both contact surfaces. Extruded lava will only alter the lower contact surface, if any noticeable alteration occurs at all.

3) **Crystal Differentiation:** If the intruded magma cools over a sufficiently long time, the first crystals (of mafic composition) will crystallize first and sink out, followed by successive mineral types as cooling progresses. (Figure 5) Lava flows cool sufficiently quickly that this crystal differentiation does not occur.

4) **Crystal Size:** In general, magmas cool slower at depth and thus tend to have larger crystals, as crystal growth is not quenched by rapid cooling. Extruded lavas cool quickly and typically consist of small crystals. This criterion in only generally applicable -- if the chemical compostions of the extruded and intruded rocks are significantly different, this general relation may no longer hold.

What We Will See

A topographic map (Figure 6) and a geologic map (Figure 7) of the region we will be viewing provides a good stating place for understanding what we'll see.

Upstream we should be able to see some Paleozoic rocks, overlain by Tertiary gravels and capped with a lava flow. Downstream we should see Dripping Spring Quartzite at river level, overlying Mescal Limestone, and diabase exposed primarily in sills. We should be able to also see some abandoned asbestos mines at the contact between the diabase and the Mescal Limestone. The island is Dripping Springs Quartzite.

We should also be able to see the Mule Hoof Monocline (Figure 7) exposed in the north canyon wall with about 50m of structural relief. Rocks exposed in the monocline include the Dripping Springs Quartzite, Mescal Limestone, and diabase. The diabase intrudes both the quartzite and limestone along bedding plans and faults.

The river course is controlled by its ability to erode the local rocks. Here the river cuts into diabase, which is weaker than the bounding quartzite. The folding of Apache Group rocks has forced the river to make two sharp turns as it enters and leaves the monocline. This may or may not be apparent. Mule Hoof Bend itself is an incised meander. (Davis, et al.)

Intrusive and Extrusive Volcanism in the Solar System

Determining Magma Generation Rates

As a concept, determining a magma generation rate for a planet is simple: add up all the magma that has been generated over a planet's volcanically active period and divide by the time duration of that period.

Well, getting accurate ages for planetary bodies is not as easy as it sounds. If you're lucky, you have samples to date. If not, you rely on crater counting and stratigraphic relations.

Of course, determining the amount of magma that has been generated is also non trivial. Estimates of the thickness of surface features must be made to compute volumes, and these surface features may be eroded or covered once they are formed. And, even more importantly, ***EXTRUSIVE MAGMATISM IS ONLY A FRACTION OF ALL OF THE MAGMA PRODUCED!*** So, how do we get information about intrusive volcanism, when by definition, it is not extruded so we can't see it?

Never the less, despite these obstacles, scientists have braved onward and determined

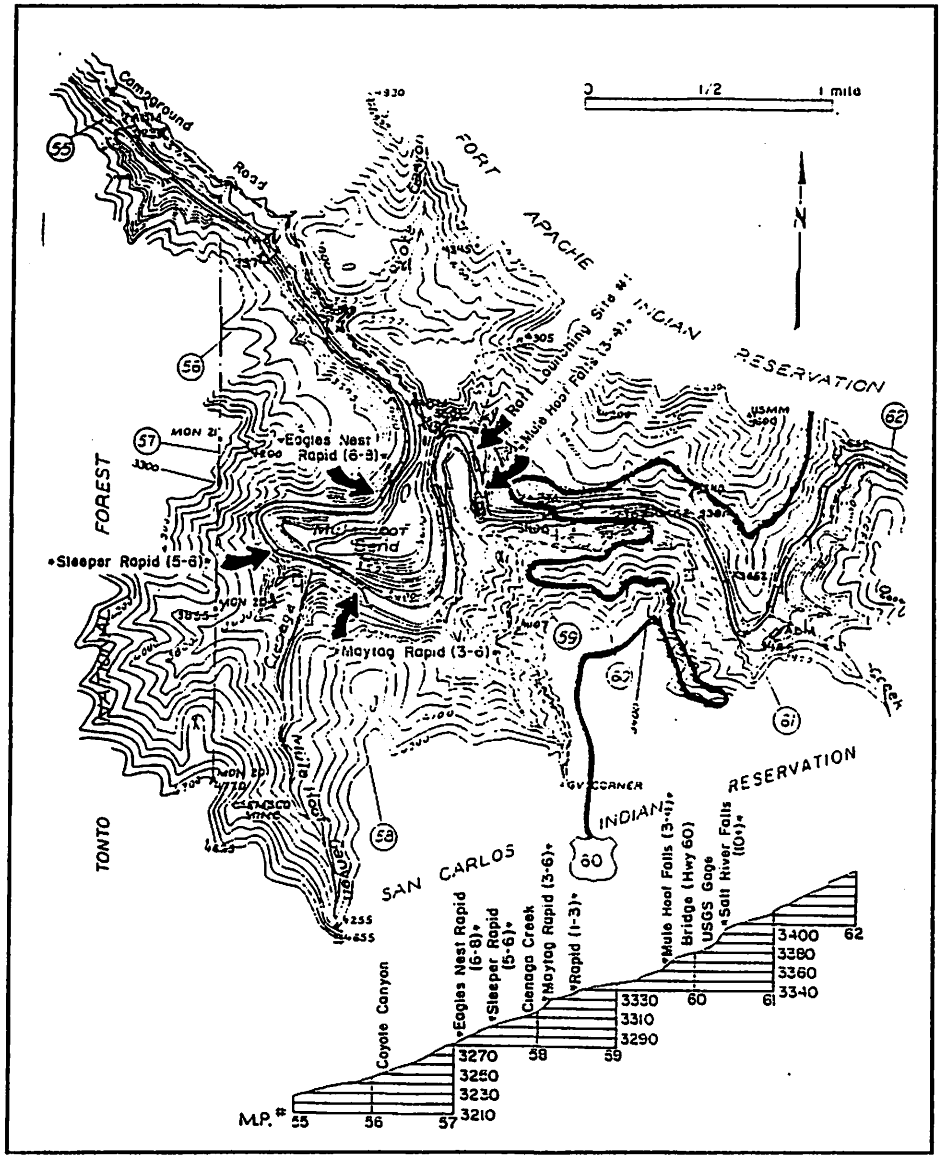


Figure 6 - Topographic map of the Mule Hoof Bend area. (from Davis, et al.)

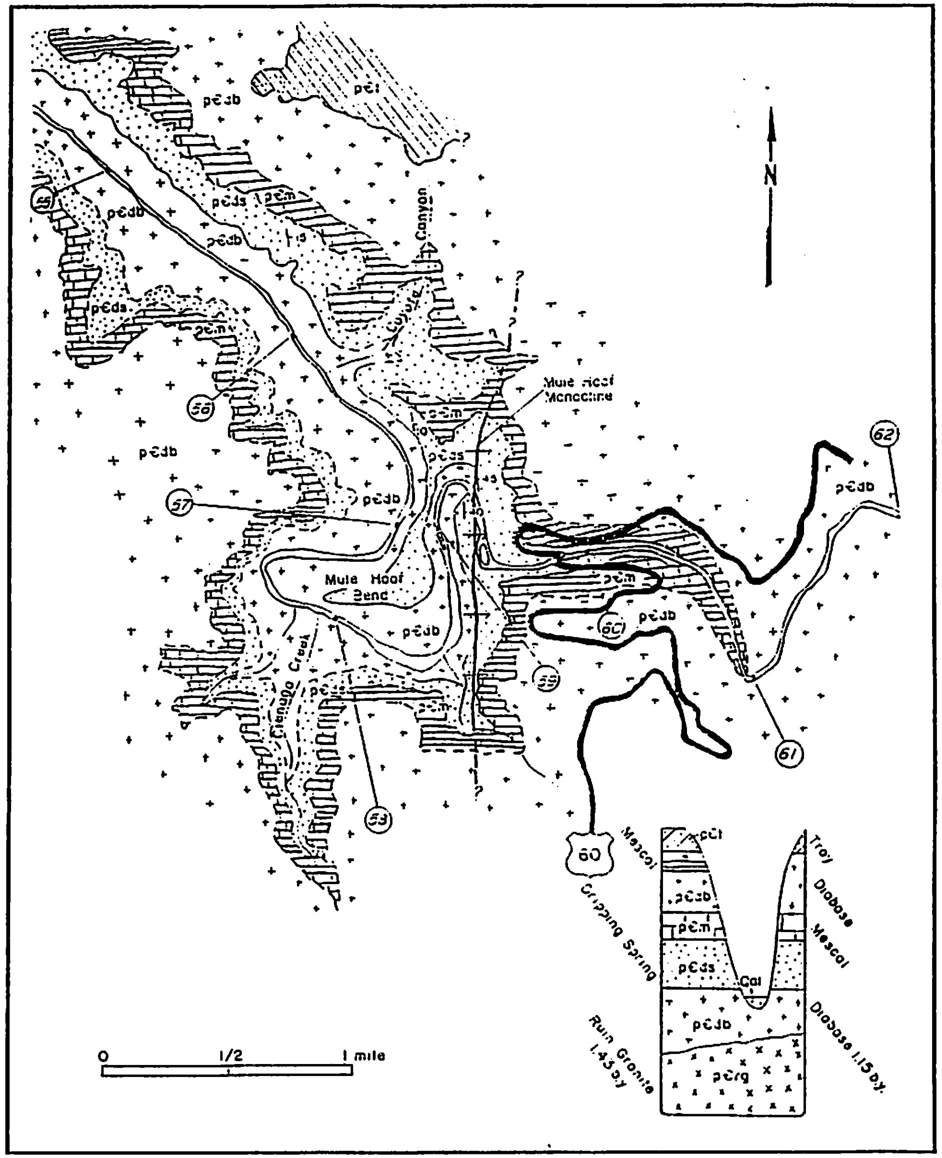


Figure 7 - Geologic map of the Mule Hoof Bend area. (from Davis, et al.)

MOON

(from Head and Wilson)

Method: observe 17% of lunar surface covered. See Figure 9 for ways to estimate thickness to get volume. Age from crater counts, dating of samples. "cryptomare" detected from intermediate albedo surfaces, so maybe 20% of surface is covered?

Result: difference between near and farside explained because of thicker crust on farside; **maximum intrusive to extrusive ratio of 50:1 because otherwise would detect higher observed crustal density**; ascent and eruption influenced by magma buoyancy, crustal thickness, topography, thermal evolution trends....; 0.0024 km^3/yr extrusive production.

VENUS

(from Grimm and Solomon)

Method: determine age of surface form retention age of craters; compare to what crater count should be for a surface that age - missing craters are attributed to being obliterated by volcanic activity to give an upper limit

Result: maximum of 2 km^3/yr volcanic resurfacing rate; no intrusive to extrusive considerations

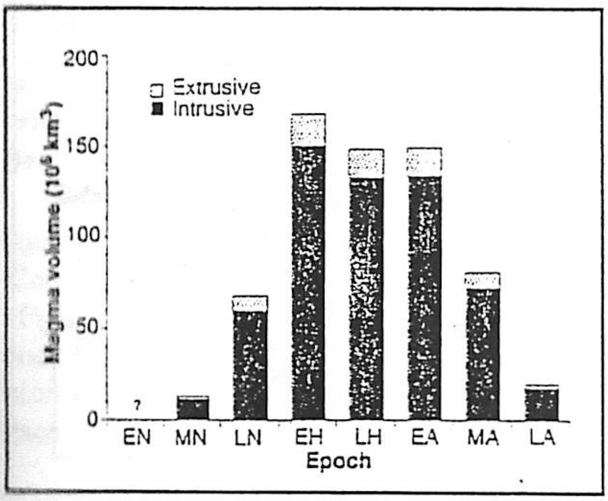


Figure 10 - Magma production rates on Mars. (from Greely and Schneid)

MARS

(from Greely and Schneid)

Method: measure areal extent (46% of surface); estimate (guess) thickness; ages from crater counting; "extrapolate volcanic volumes by age for areas covered by younger rocks"; use 8.5:1 for intrusive to extrusive calculation.

Result: total magma production: 0.17 km^3/yr; (Figure 10); applied this intrusive to extrusive ratio also to above Moon and Venus numbers; (Table 1).

Table 1: Magma production rates

Planetary Body	Extrusive Rate (km^3/yr)	Total Magma Production (km^3/yr)
Earth	3.9	30
Moon	0.0024	0.025
Venus	≤ 2	≤ 19
Mars	0.018	0.17

THE POINT (or just using 8.5:1 is not good enough)

Much of the magma produced on planetary bodies is intrusive. Any assumptions therefore made about intrusive to extrusive ratios will significantly affect resulting calculations and conclusions. So what can we do to make good estimates of intrusive to extrusive ratios? Understanding the factors that control magma emplacement and observing the types of extrusive features we do and do not see are probably the best bets.

Spheroidal Weathering

Spheroidal weathering is a fairly straightforward process that results in all of those nifty freestanding rounded boulders we magma generation rates for the Earth, Moon, Venus and Mars. How did they do it? Well, by gathering some data and then by making the rest of it up.

EARTH

(from Crisp)

Method: areal mapping and field observations (for extrusive); geophysical methods, spreading rates, and observations from erosion (for intrusive); ages from dating techniques

Result: ratio of intrusive to extrusive volcanism between 3:1 and 16:1; (see Figure 8); dependent on crustal thickness, magma composition, tectonic setting, regional stress.....; 75% of total is from ocean-ridge magmatism. 26-34 km^3/yr = total global magmatism.

Intracontinental	
Yellowstone	4:1--10:1
Oslo, Norway	<16:1
Caldera-forming ash-flow reservoirs	~10:1
Twin Peaks, Utah	5:1—9:1
Subduction-zone related	
Andes	~6:1[b]
Peru	<13:1[b]
Kurile Islands	<13:1[b]
Kaimondake, Japan	0.8:1[c]
Fuego, Guatemala	1:1 to 2.1:1
"Typical" stratovolcano	1.5:1[c]
Oceanic	
Kilauea	5:1
Hawaii	≤5:1
Average for mid-ocean ridge	≅6:1
Iceland	3:1—6:1

Figure 8 - Ratios of intrusive to extrusive volumes. (from Crisp)

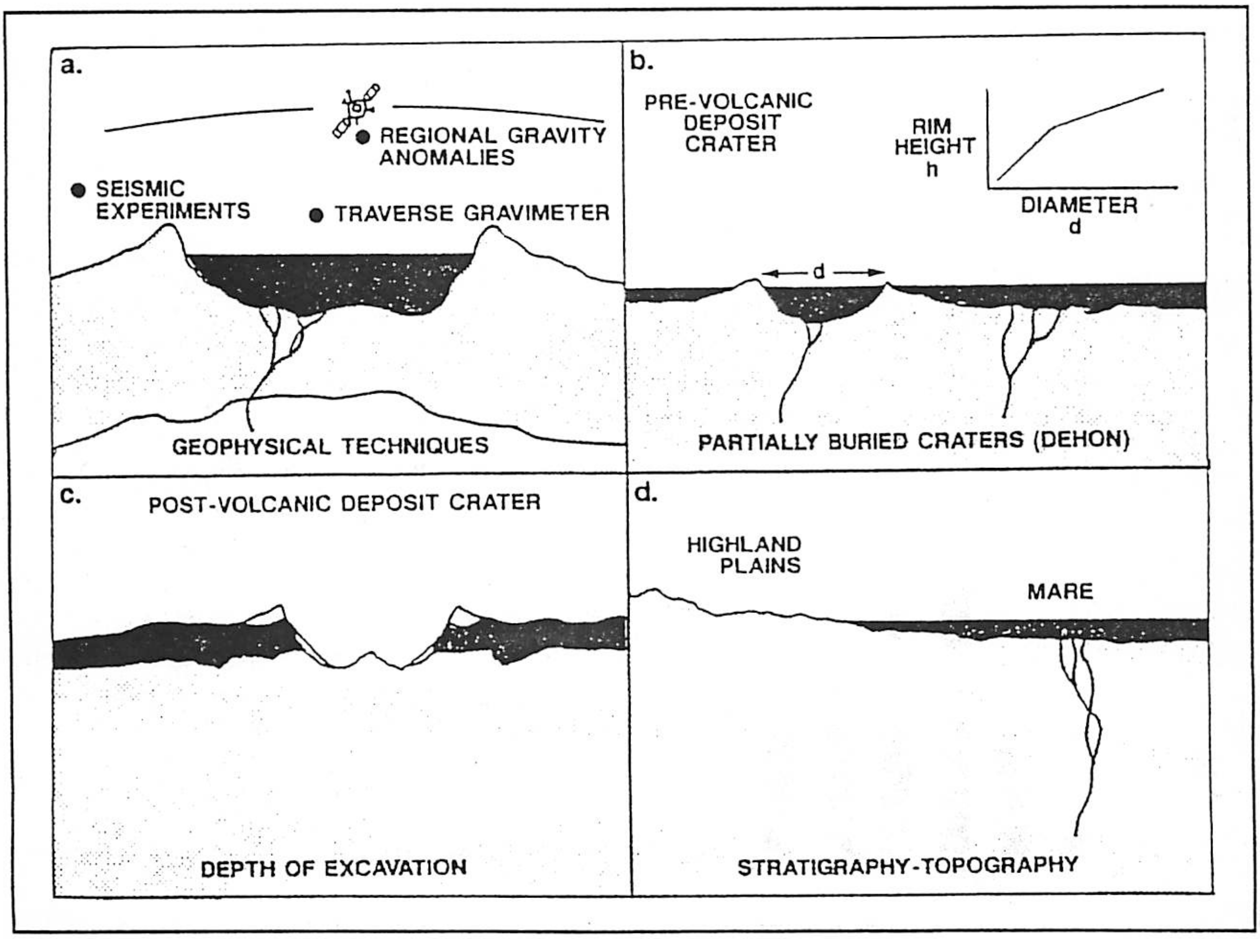


Figure 9 - Estimating thickness of extrusive lavas. (from Head and Wilson)

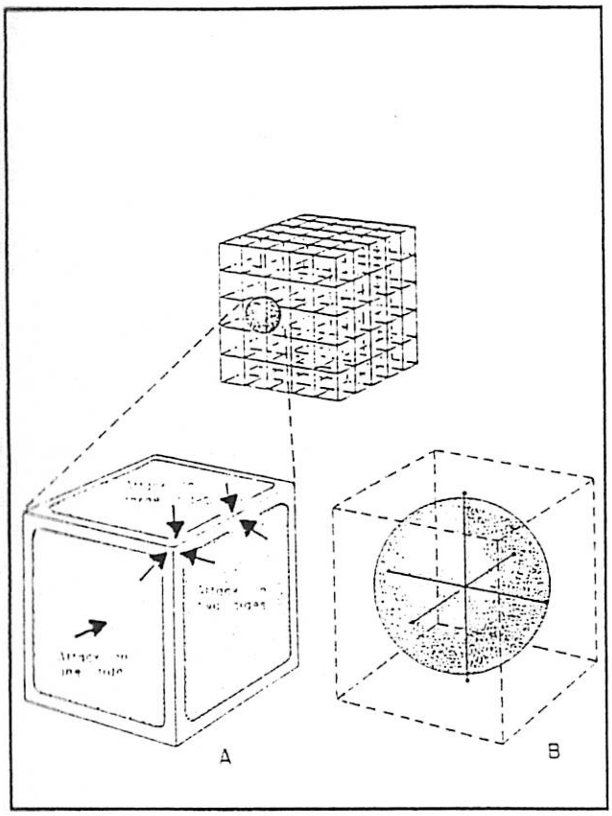


Figure 11 - Geometry of spheroidal weathering. (from Ferry)

see at Texas Canyon and other places along our trip. Formation of these features requires these three major conditions to exist:

1) A homogeneous, basically unlayered rock with a significant amount of feldspar and mineral crystals that are all about the same size.

2) Rainwater (rain + CO_2 in air = acid rainwater with dissolved CO_2; feldspar + acid rainwater = clay + dissolved stuff; feldspar = hard mineral, clay = soft and crumbly)

3) Network of planar fractures or joints (rainwater acts along these fractures. Corners become rounded; surfaces exfoliate. (Figure 11) The material weathered from the rock forms a soil called grus. Subsequent erosion exposes the rounded boulders at the surface. (Figure 12)

Granite is the dominant victim of spheroidal weathering, at least in Arizona, and we see such weathering products at Texas Canyon.

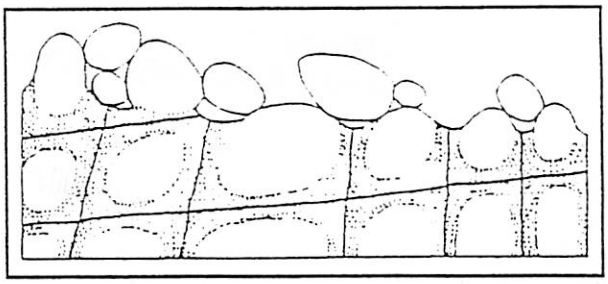


Figure 12 - Stages in the exposure of rounded boulders. (from Ferry)

Diabase in the Salt River Canyon also weathers in this fashion, so we should see some of that later in our trip.

The Rise of the English Parliamentary System

You mean you actually read this far?

References

Crisp, *J. Volcan. and Geotherm. Res.*, p177, 1984.

Ferry, J. M., Landforms of Spheroidally Weathered Rock, in *Lanforms of Arizona*, 415-427, 1984.

Greeley and Schneid, *Science*, p254, 1991.

Grimm and Solomon, *Geophys. Res. Let.*, p538, 1987.

Head and Wilson, GCA, p2155, 1992.

Plummer, Charles C. and McGeary, D. *Physical Geology*, Wm. C. Brown Publishers, 1981.

Davis, G. H., Showalter, S. R., Benson, G. S., McCalmont, L. S., Cropp, F. W. III, Guide to the Geology of the Salt River Canyon Region, Arizona. *Arizona Geological Society Digest* 13:48-97, 1981.