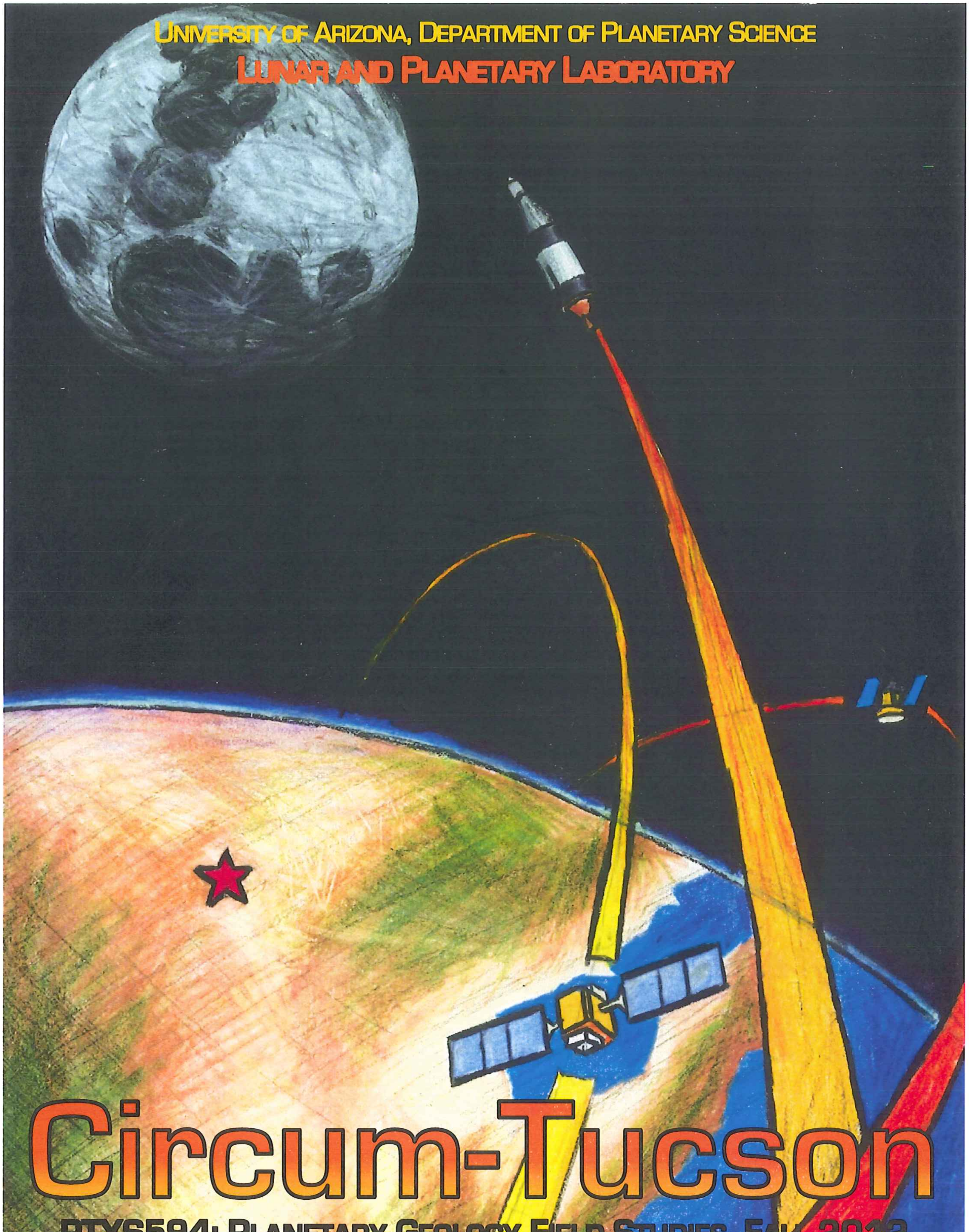

University of Arizona, Department of Planetary Science

Lunar and Planetary Laboratory

Circum-Tucson

PTYS594: Planetary Geology Field Studies, Fall 2012

Letter from the Editor

Geology.
It's awesome.

James Tuttle Keane,
editor

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PTYS 594 – Fall 2012 – Circum-Tucson (10/26-10/28)

Day 1 Itinerary

8am Leave LPL
9am Arrive at stop 1: The Pirate Fault in Saddlebrook

- Youngmin: Farallon plate activity in the Cretaceous and Tertiary
- Kat: Basin and Range Formation

10am Leave Pirate Fault
11.15am Arrive at stop 2:Bear Canyon Pediment

- Robert: Debris flows (*)
- Sarah: Pediments
- Ning: Joint formation and control on valley creation (*)

12.30pm Leave Bear Canyon Pediment
1PM Arrive at stop 3: Bear Canyon Picnic Area

- Lunch
- Ethan: Grussification of granite and spheroidal weathering

2pm Leave Bear Canyon Picnic Area
2.05pm Arrive at stop 4: Windy Point

- Corey: Rock Metamorphism (Schist, Gneiss etc…)
- Cecilia: Mylonite and cataclastic deposits (*)

3pm Leave Windy Point
3.15pm Arrive at stop 5: Upper Soldier Canyon

- Jamie: Detachment-limited erosion in mountain channels
- Ning: Joint formation and control on valley creation (*)

4.15pm Leave Upper Soldier Canyon
4.30pm Arrive at stop 6: Recent Debris flows just off Catalina Highway

- Robert: Debris flows (*)

4.50pm Leave recent debris flows
5.40pm Arrive at Camp 1: Reddington Pass (Elevation ~4400')

- Sunset is at 5.40pm

Day 2 Itinerary

8am Leave Camp
10am Arrive at stop 7: The Catalina Detachment Fault

- James: Broader view of metamorphic core complexes and their recognition
- Donna: Detachment faulting and the Catalina Detachment Fault
- Cecilia: Mylonite and cataclastic deposits **(*)**
- Lunch

12pm Leave Catalina Detachment Fault
1pm Arrive at stop 8: at Earth Fissure Site

- Christa: Alluvial Fans and Bajadas
- Kelly: Tucson's groundwater overdraw and giant martian polygons

2pm Leave Earth Fissure Site
3.30pm Arrive at stop 9: St. David Formation

- Melissa: San Pedro river terraces and Saint David formation
- Corrianne: Fossils of San Pedro Valley

4.30pm Leave St. David Formation
5.45pm Arrive at camp 2 in the Whetstone mountains (Elevation 4400-5000')

- Sunset is at 5.40pm

Day 3 Itinerary

8am Leave Camp
8.15am Arrive at stop 10: Kartchner Caverns

- Ali: Limestone dissolution and cave formation
- Binna: Local history – post ice-age to Spanish missions
- Cave tours: Starts 9.15am and 9.45am, lasts 90 minutes.

11.30am Leave Kartchner Caverns
12.45am Arrive at stop 11: Gates Pass Area

- Lunch
- Davin: Pyroclastic volcanism and tuff formation
- Catherine: Caldera collapse and megabreccia in the Tucson Mountains

2pm Leave Gates Pass
2.15pm Arrive Kings Canyon Trailhead

- Hike the Gould Mine Trail (~2.5 miles roundtrip) stop at dikes, amole arkose and the mine.
- Michelle: Hydrothermal (and dike) mineralization and ore formation
- Dyson: Mining in the Tucson area: history and current controversy

4.45pm Leave Kings Canyon Trailhead
5pm Arrive at multi-contact hill and/or Sus Picnic Area.

- See contacts of Paleozoic Sediments and Amole Granitic Pluton

6pm Return to LPL

Participants

Atwood-Stone, Corey
Boumis, Robert
Bramson, Ali
Bray, Veronica
Byrne, Shane
Chung, Youngmin
Ding, Ning
Dykhuis, Melissa
Dyson, Dyson
Elder, Catherine
Flateau, Davin
Keane, James
Kim, Binna
Lamkin, Corrianne
Leung, Cecilia
Miller, Kelly
Molaro, Jamie
Morrison, Sarah
O'Brien, Dave
Schaefer, Ethan
Spitale, Joe
Thompson, Michelle
Van Laerhoven, Christa
Viola, Donna
Volk, Kat


Oracle
San Manuel
Mt Lemmon
Santa Catalina Natural Area
Mica Mountain
Tanque Verde
Saguaro National Park
Catalina
Catalina State Park
Oro Valley
Casas Adobes
Catalina Foothills
Tucson
Tortolita
Tortolita Mountain Park
Marana
Picture Rocks
Tucson Mountain Park
Tucson Estates
Drexel Heights
Sahuarita
Green Valley
Vail
Benson
77
10
19
90
191
10 mi
10 km

Sunrise & Sunset (and Moonrise & Moonset)

Daily events for Friday, 26 October

Event:	Time:	Altitude:	Azimuth:	
Astronomical twilight begins:	05:14	-18.0°	94°	
Nautical twilight begins:	05:42	-12.0°	98°	
Civil twilight begins:	06:11	-6.0°	101°	
Sunrise:	**06:36**	**-0.8°**	**105°**	
Maximum altitude:	12:07	45.0°	180°	
Sunset:	**17:38**	**-0.8°**	**255°**	
Civil twilight ends:	18:04	-6.0°	259°	
Nautical twilight ends:	18:32	-12.0°	262°	
Astronomical twilight ends:	19:01	-18.0°	266°	
Minimum altitude:	23:59	-70.6°	354°	
Moon: Rise:	15:54	0.1°	85°	
Moon: Maximum Altitude:	22:13	63.1°	181°	*91%*
Moon: Set	03:40	0.1°	272°	*illuminated*

Daily events for Saturday, 27 October

Event:	Time:	Altitude:	Azimuth:	
Astronomical twilight begins:	05:15	-18.0°	94°	
Nautical twilight begins:	05:43	-12.0°	98°	
Civil twilight begins:	06:12	-6.0°	102°	
Sunrise:	**06:37**	**-0.8°**	**105°**	
Maximum altitude:	12:07	44.7°	180°	
Sunset:	**17:37**	**-0.8°**	**255°**	
Civil twilight ends:	18:03	-6.0°	258°	
Nautical twilight ends:	18:32	-12.0°	262°	
Astronomical twilight ends:	19:00	-18.0°	265°	
Minimum altitude:	23:59	-71.0°	354°	
Moon: Rise:	16:27	0.1°	80°	
Moon: Maximum Altitude:	22:57	67.4°	181°	*96%*
Moon: Set	04:36	0.1°	277°	*illuminated*

Daily events for Sunday, 28 October

Event:	Time:	Altitude:	Azimuth:	
Astronomical twilight begins:	05:15	-18.0°	95°	
Nautical twilight begins:	05:44	-12.0°	98°	
Civil twilight begins:	06:13	-6.0°	102°	
Sunrise:	**06:38**	**-0.8°**	**105°**	
Maximum altitude:	12:07	44.3°	180°	
Sunset:	**17:37**	**-0.8°**	**254°**	
Civil twilight ends:	18:02	-6.0°	258°	
Nautical twilight ends:	18:31	-12.0°	261°	
Astronomical twilight ends:	18:59	-18.0°	265°	
Minimum altitude:	23:59	-71.3°	354°	
Moon: Rise:	17:01	0.1°	76°	
Moon: Maximum Altitude:	23:42	71.2°	181°	*99%*
Moon: Set	05:31	0.1°	282°	*illuminated*

From
Heavens-Above.com

Satellite Predictions

Satellite Predictions (<3.5 mag)for the night of Friday, 26 October

Satellite	Brightnes s (mag)	Start			Highest point			End		
		Time	Altitude	Azimuth	Time	Altitude	Azimuth	Time	Altitude	Azimuth
Cosmos 1626	2.6	17:57:43	10°	N	18:01:28	43°	E	18:05:11	10°	SSE
ATLAS 2A CENTAUR R/B	3.4	18:02:27	10°	WSW	18:06:07	45°	S	18:21:16	10°	ESE
SL-16 R/B	2.9	18:06:56	10°	NNE	18:12:46	42°	E	18:18:35	10°	S
Cosmos 1455 Rocket	3.4	18:16:44	10°	N	18:21:00	43°	E	18:25:13	10°	SSE
SKYMED 2	3.5	18:26:37	10°	NNE	18:30:57	77°	ESE	18:35:16	10°	S
CZ-2C R/B	3.4	18:35:47	10°	NNE	18:40:21	35°	E	18:44:43	10°	SSE
H-2A R/B	3.1	18:40:04	10°	N	18:44:05	57°	WNW	18:48:15	10°	SSW
Cosmos 1726	2.9	18:41:14	10°	SSE	18:44:43	32°	E	18:47:19	16°	NE
Cosmos 1455	2.2	18:42:48	10°	S	18:46:40	60°	E	18:50:33	10°	NNE
H-2A ROCKET BODY	2.5	18:45:14	10°	W	18:59:39	60°	SSW	19:01:32	29°	ESE
Cosmos 1862	3.4	18:46:20	10°	N	18:50:26	80°	W	18:54:29	10°	S
Cosmos 1263 Rocket	1.6	18:47:42	10°	SSW	18:50:30	69°	W	18:53:13	10°	N
ISS	**-0.7**	**18:48:31**	**10°**	**NNE**	**18:48:44**	**10°**	**NNE**	**18:48:44**	**10°**	**NNE**
Cosmos 1943 Rocket	2.1	19:00:45	10°	SSW	19:06:21	89°	WNW	19:12:01	10°	NNE
Cosmos 1238 Rocket	3	19:10:50	10°	N	19:14:51	74°	E	19:19:55	10°	S
ADEOS II	2.1	19:12:18	18°	SE	19:16:06	54°	ENE	19:21:14	10°	N
OAO 3 Rocket	3.2	19:31:52	10°	WNW	19:36:38	73°	N	19:36:38	73°	N
Cosmos 2227 Rocket	3.2	19:36:20	10°	N	19:39:30	31°	NNE	19:39:30	31°	NNE

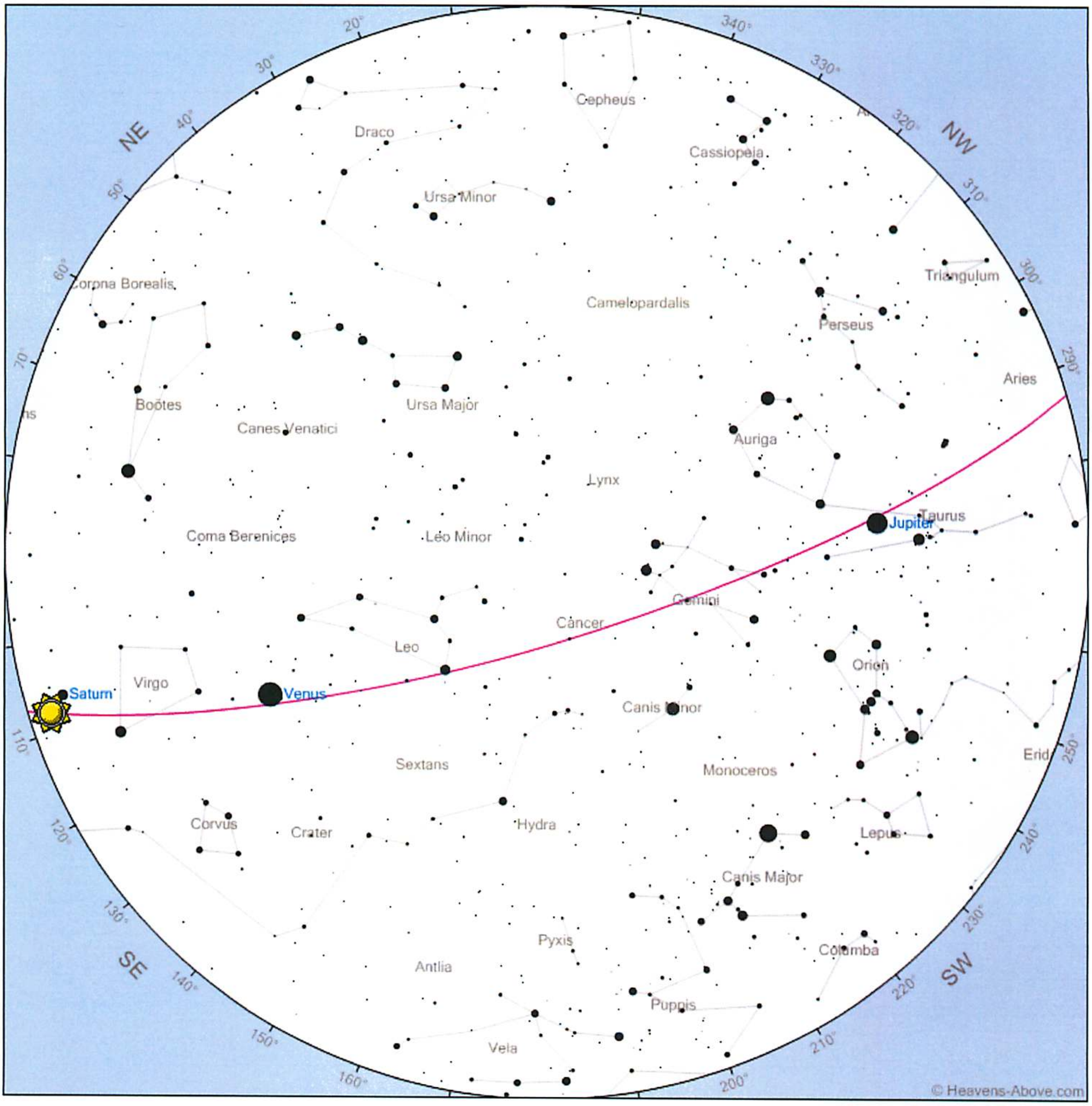
Satellite Predictions (<3.5 mag)for the night of Saturday, 27 October

Satellite	Brightnes s (mag)	Start			Highest point			End		
		Time	Altitude	Azimuth	Time	Altitude	Azimuth	Time	Altitude	Azimuth
Resurs 1-4 Rocket	3.4	17:56:35	10°	S	18:01:41	48°	W	18:06:49	10°	NNW
COSMO-SKYMED 1	3.3	17:57:00	10°	NE	18:00:53	32°	E	18:04:44	10°	SSE
Okean 3	3.4	18:14:47	10°	S	18:19:05	76°	E	18:23:21	10°	N
OAO 3 Rocket	3.4	18:19:32	10°	WNW	18:24:22	63°	N	18:28:20	16°	E
Cosmos 1726	2.9	18:32:14	10°	SSE	18:35:41	31°	E	18:39:10	10°	NNE
Cosmos 1455 Rocket	3.1	18:34:28	10°	N	18:38:57	90°	W	18:43:23	10°	S
Cosmos 1455	2.2	18:36:59	10°	S	18:40:52	64°	E	18:44:47	10°	NNE
SL-16 R/B	2.5	18:37:31	10°	NNE	18:43:44	79°	ESE	18:49:57	10°	S
Cosmos 1943 Rocket	2.1	18:41:50	10°	SSW	18:47:25	80°	ESE	18:53:05	10°	NNE
ADEOS II	2.8	18:46:41	13°	SE	18:50:39	30°	ENE	18:55:11	10°	N
Cosmos 1263 Rocket	2.4	18:47:46	10°	SSW	18:50:30	47°	W	18:53:07	10°	N
Cosmos 2227 Rocket	2.7	19:21:39	10°	N	19:25:58	40°	NE	19:25:58	40°	NE
ISS	**-0.6**	**19:33:47**	**10°**	**NNW**	**19:34:24**	**14°**	**NNW**	**19:34:24**	**14°**	**NNW**

From Heavens-Above.com

Night Sky

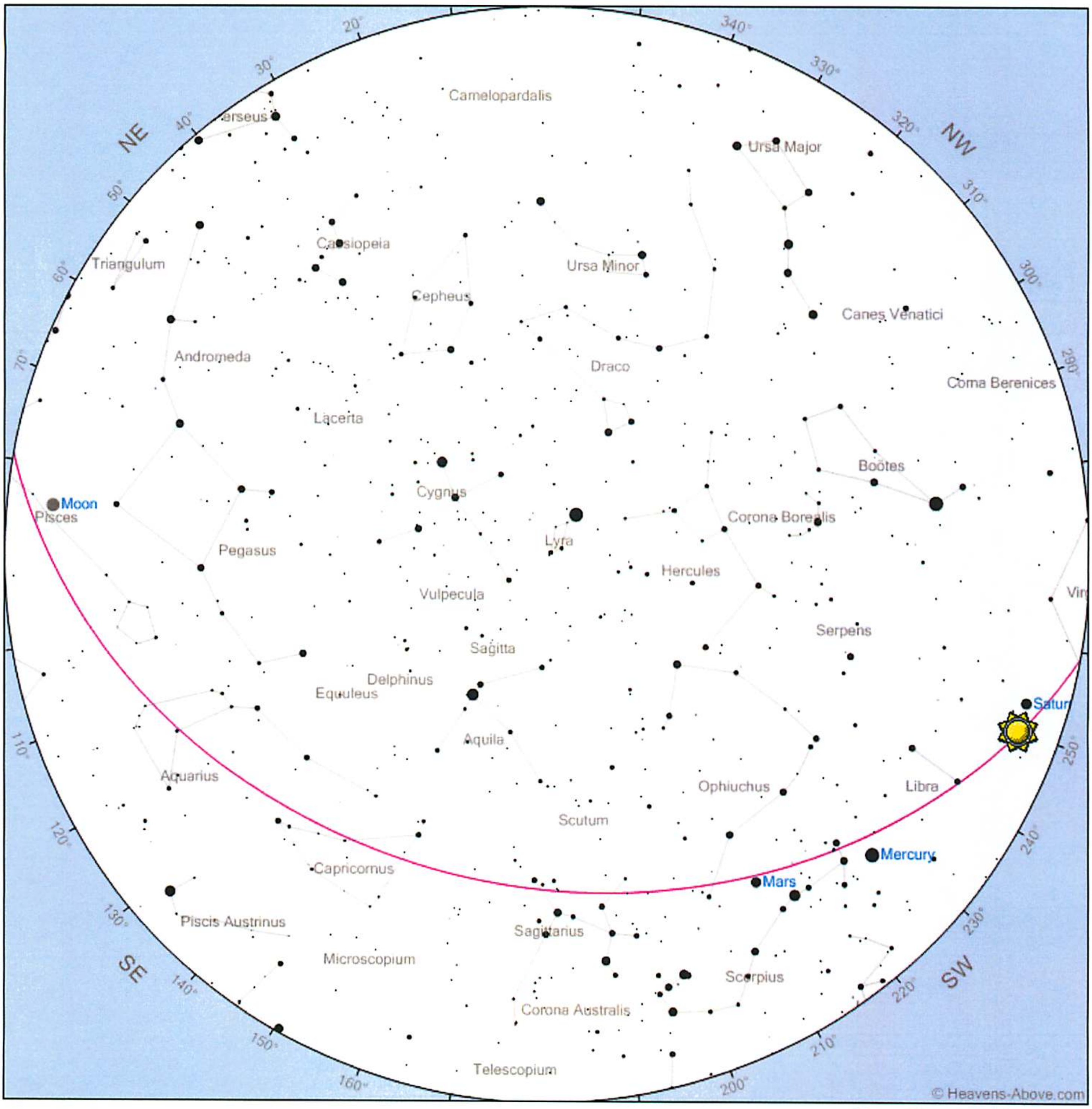
Night Sky, for Tucson on Saturday, October 27th, at 7:00 AM



From Heavens-Above.com

Night Sky

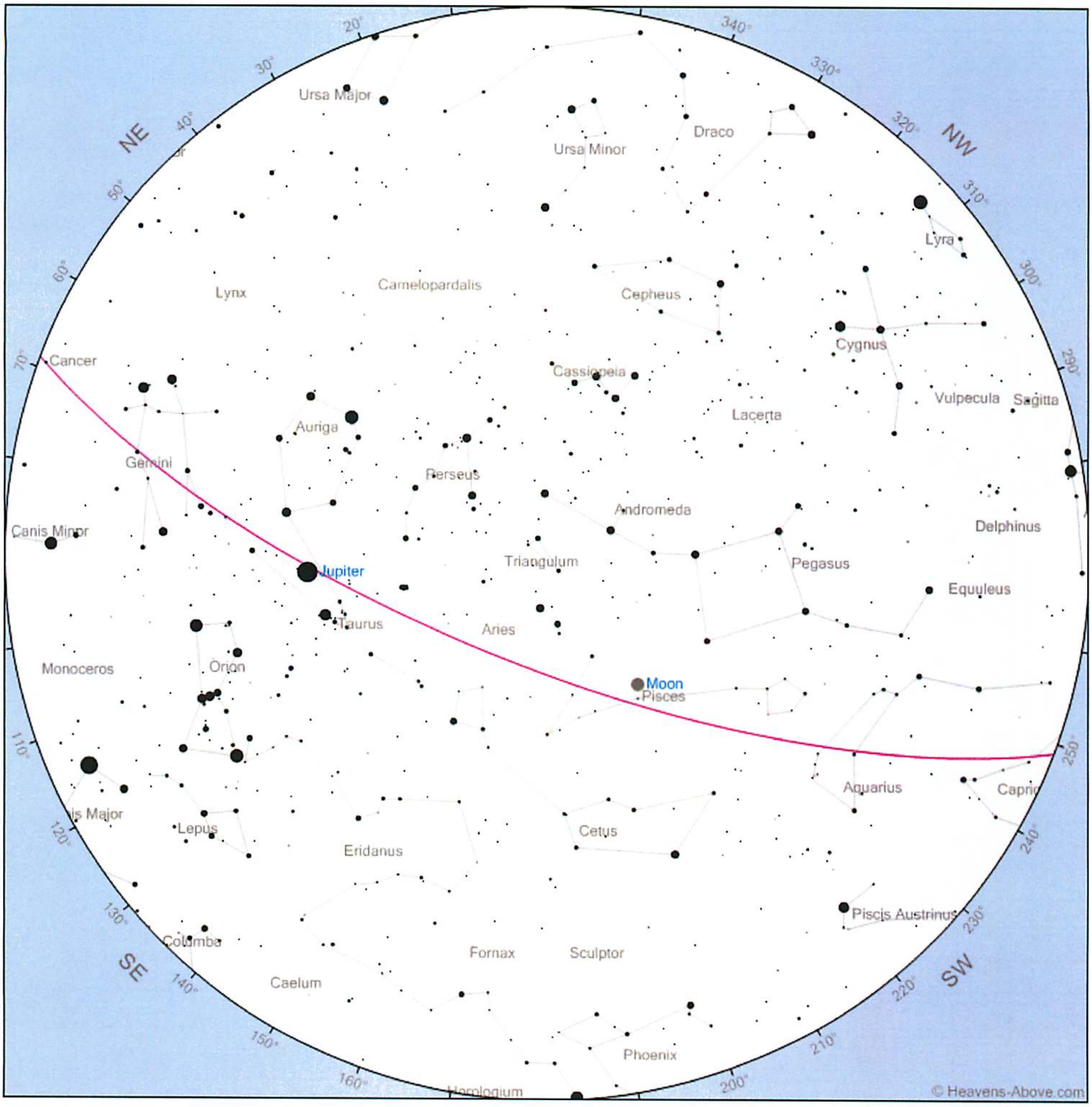
Night Sky, for Tucson on Saturday, October 27th, at 7:00PM



From Heavens-Above.com

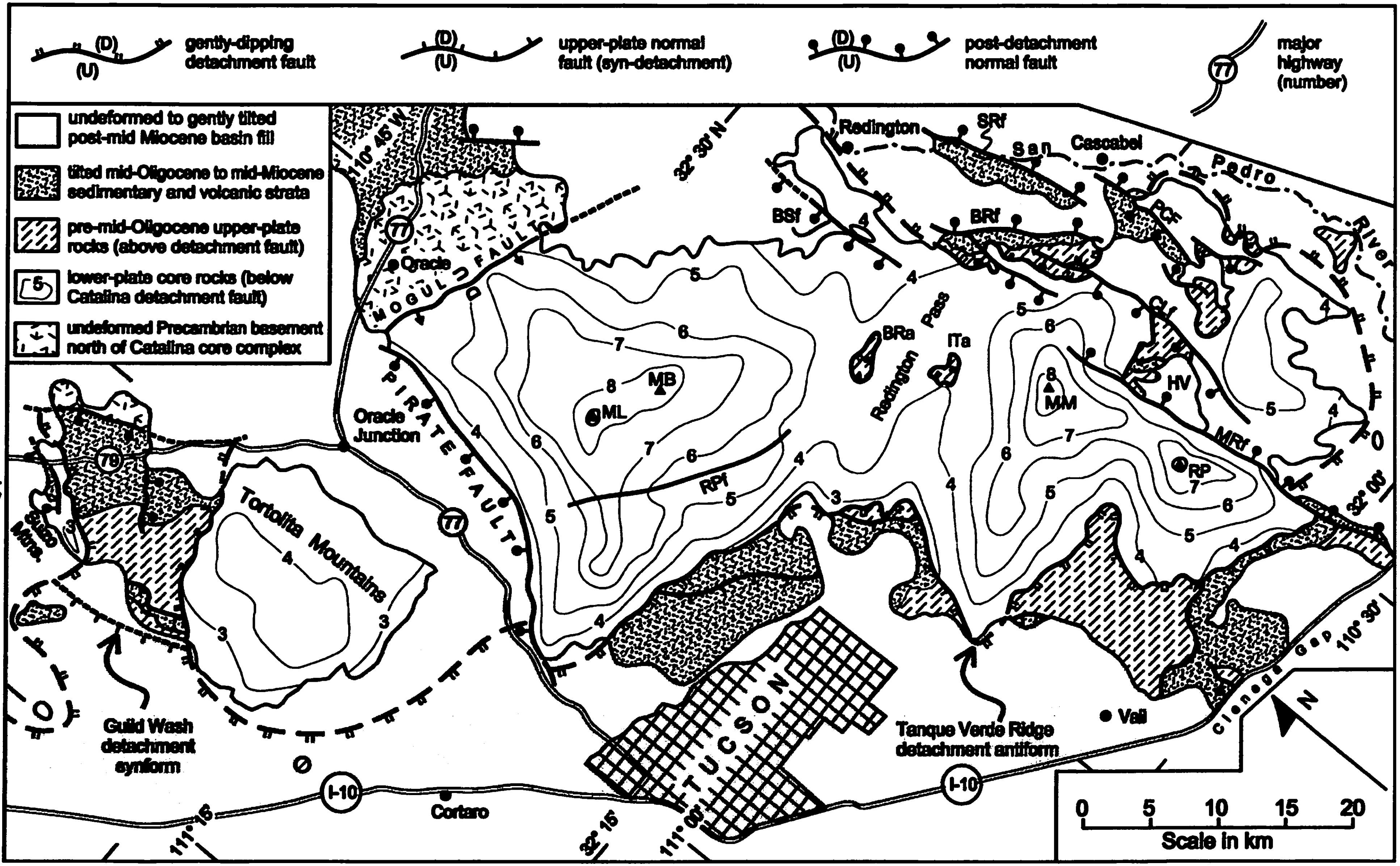
Night Sky

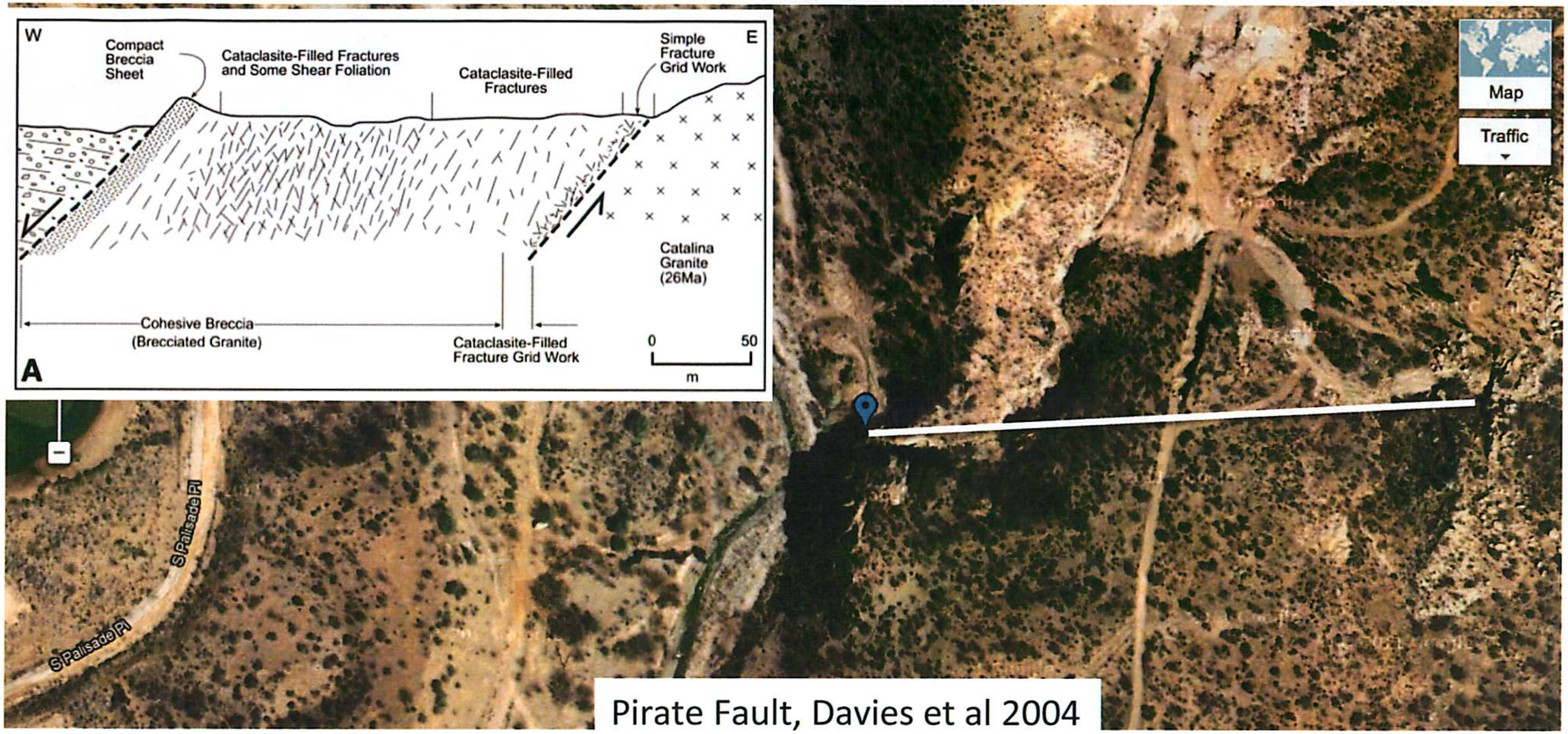
Night Sky, for Tucson on Saturday, October 27th, at 11:59PM



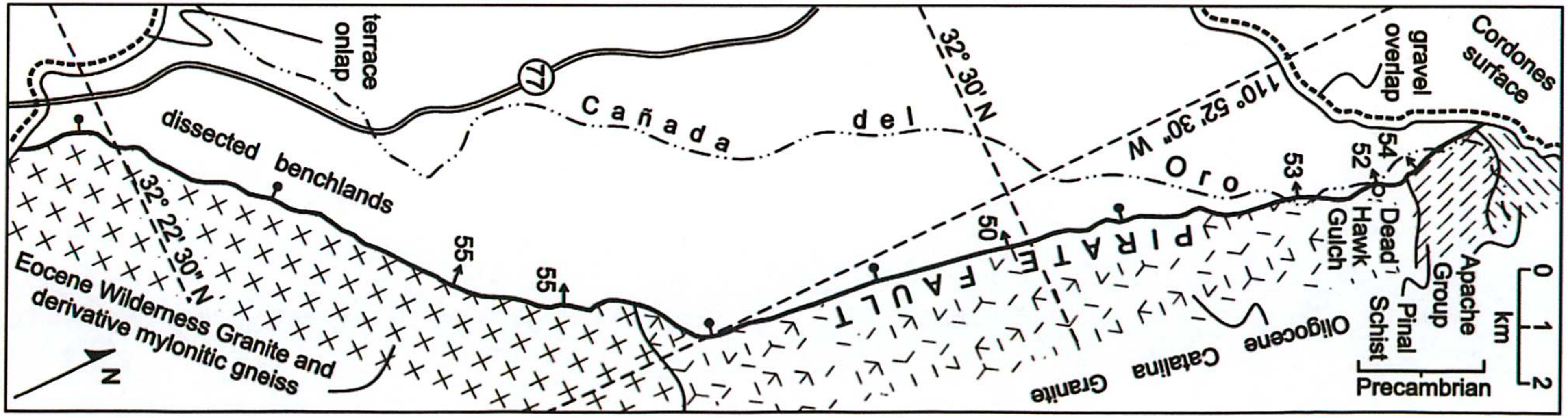
From Heavens-Above.com

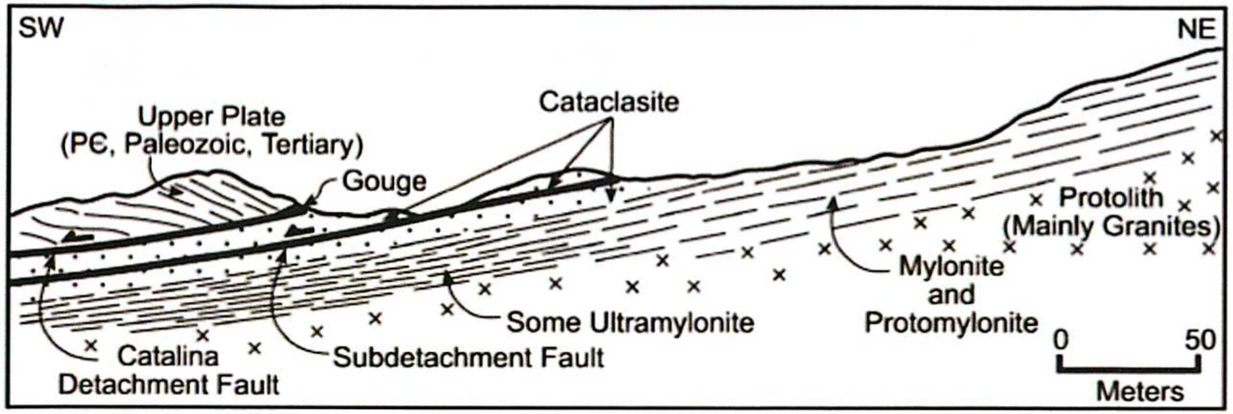
Davies et al 2004





Pirate Fault, Davies et al 2004





Catalina Detachment Fault at Salcido/Martinez Ranch

Davies et al 2004

Davies 2011

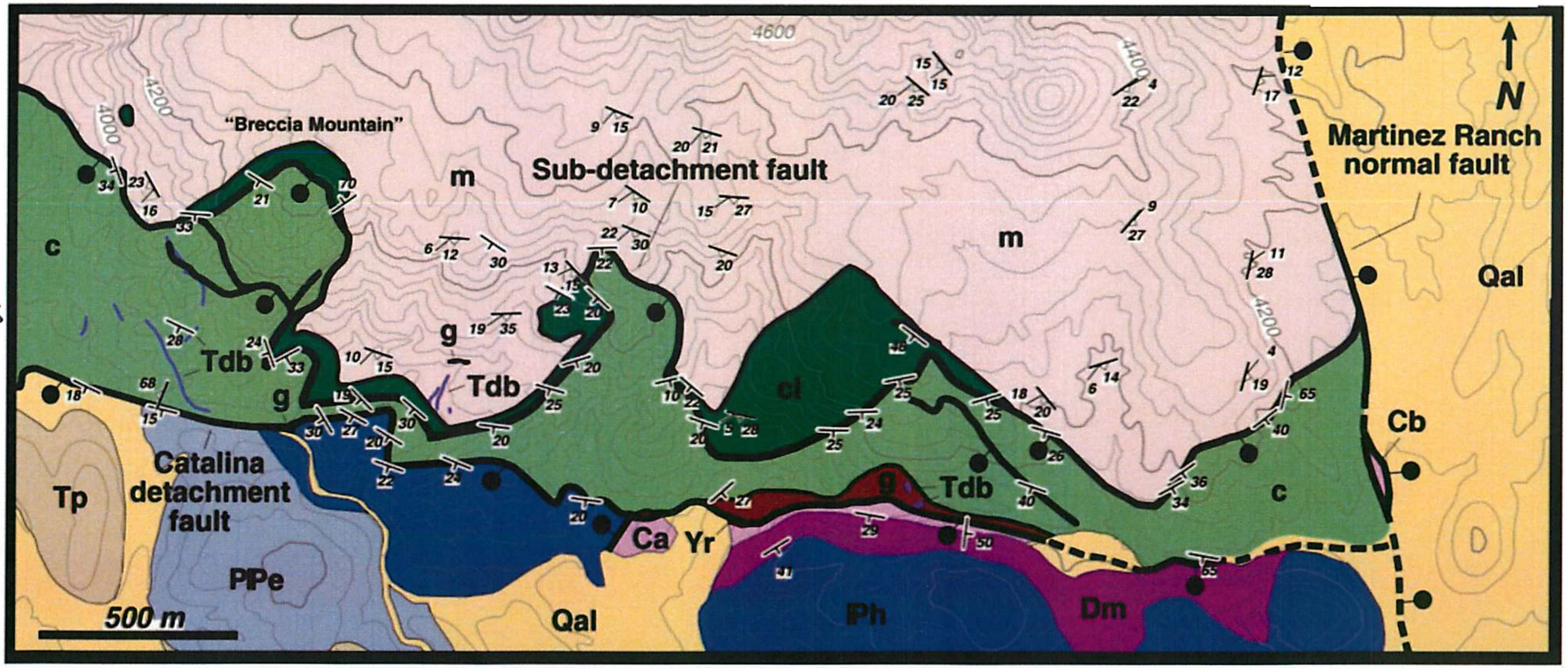


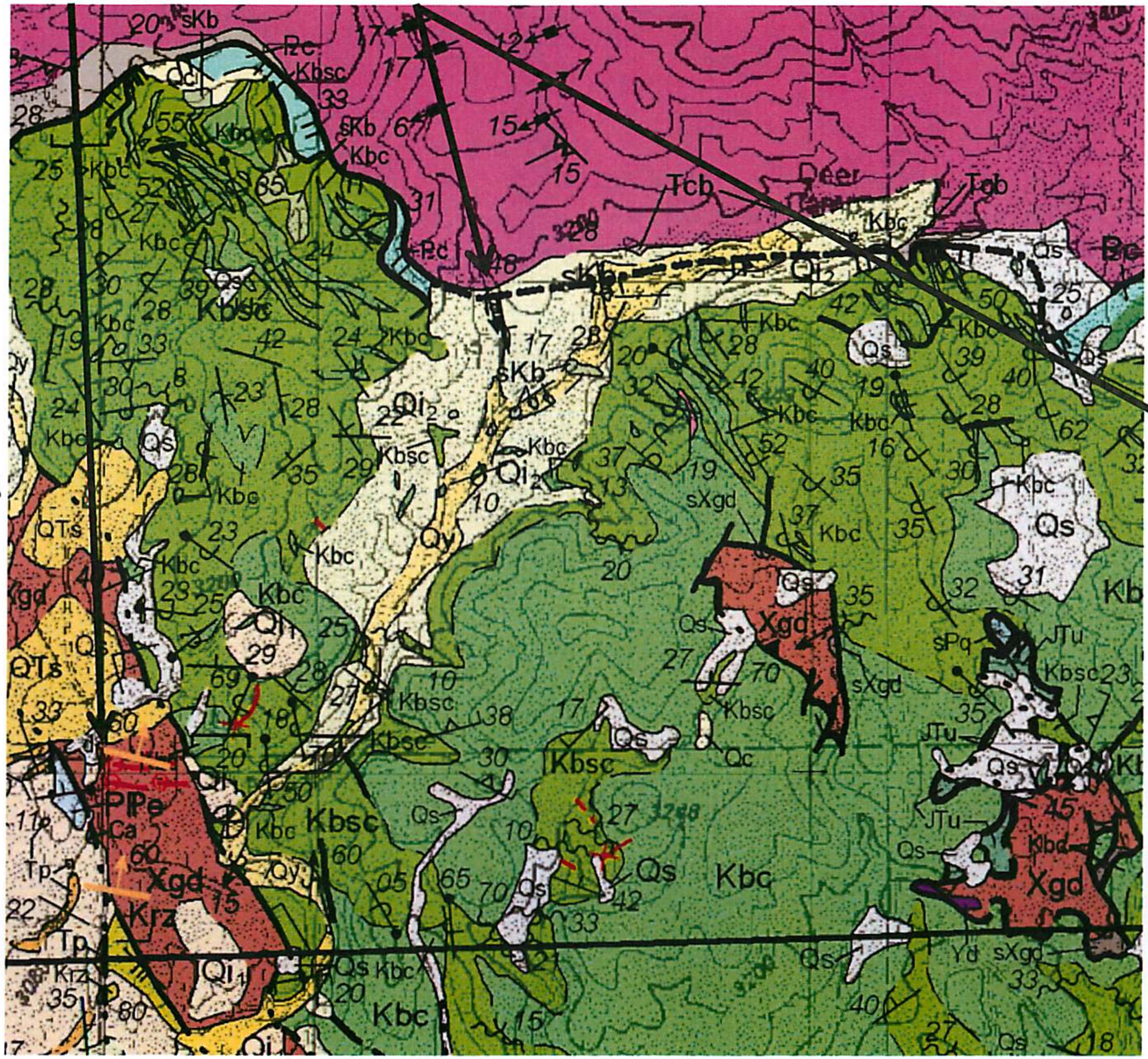
Figure 2 . Geologic map of the Salcito Ranch locality emphasizing faults and fault rocks related to the Catalina detachment fault. Key to fault-rock units (also see Table 1) : c, cataclasite, cohesive microbreccia, and breccia derived from mylonite; cl, cataclasite as above only beneath sub-detachment; g, gouge; m, mylonite, protomylonite and ultramylonite. Protolith for fault rocks is considered to be Eocene Wilderness Suite Granite (quartz monzonite). Rock unit abbreviations: Yr, Pinal Schist and Johnny Lyon Granodiorite; Cb, Cambrian Bolsa Quartzite; Ca, Cambrian Abrigo Formation; Dm, Devonian Martin Formation; Ph, Pennsylvanian Horquilla Limestone; PPe, Pennsylvanian-Permian Earp Formation; Tp, Oligocene-Miocene Pantano Formation; Tdb, Oligocene-Miocene(?) diabase dikes and sills; Qal, Quaternary alluvium. Map based on field mapping by the authors and compilation of previous mapping by Drewes 1974, 1977; Liming, 1974.

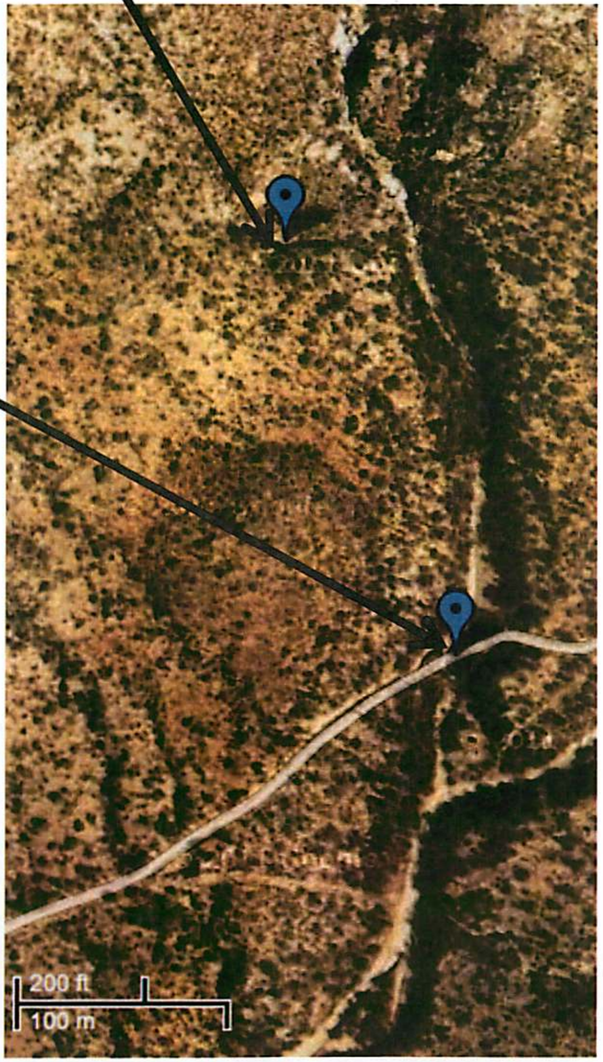
Alternate Catalina Detachment Fault Stop

East on Old Spanish Trail

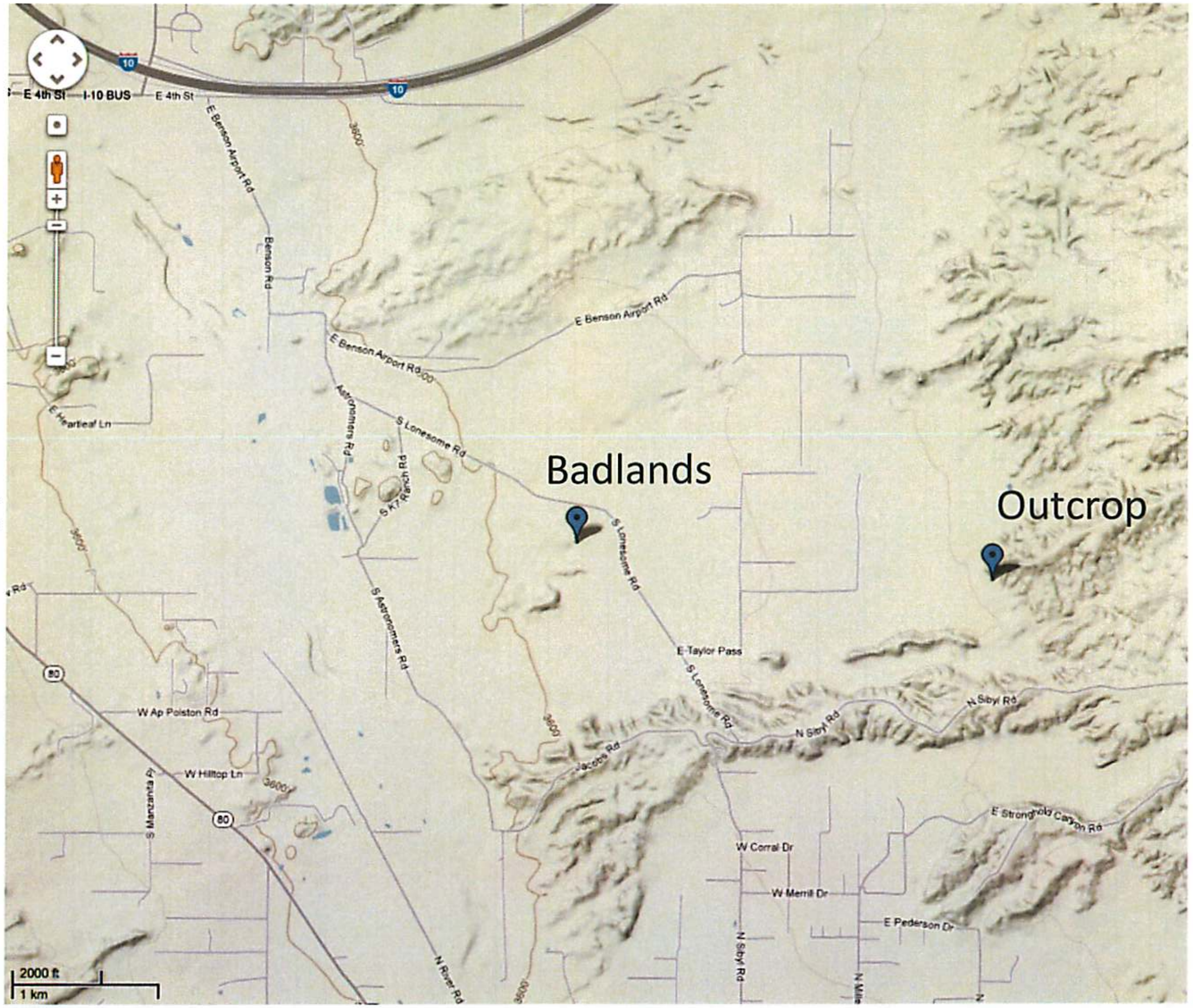
North on Camino Loma Alta

Parking — Hike east on trail until Wash — Walk up wash for ~120m then cut left for 50m

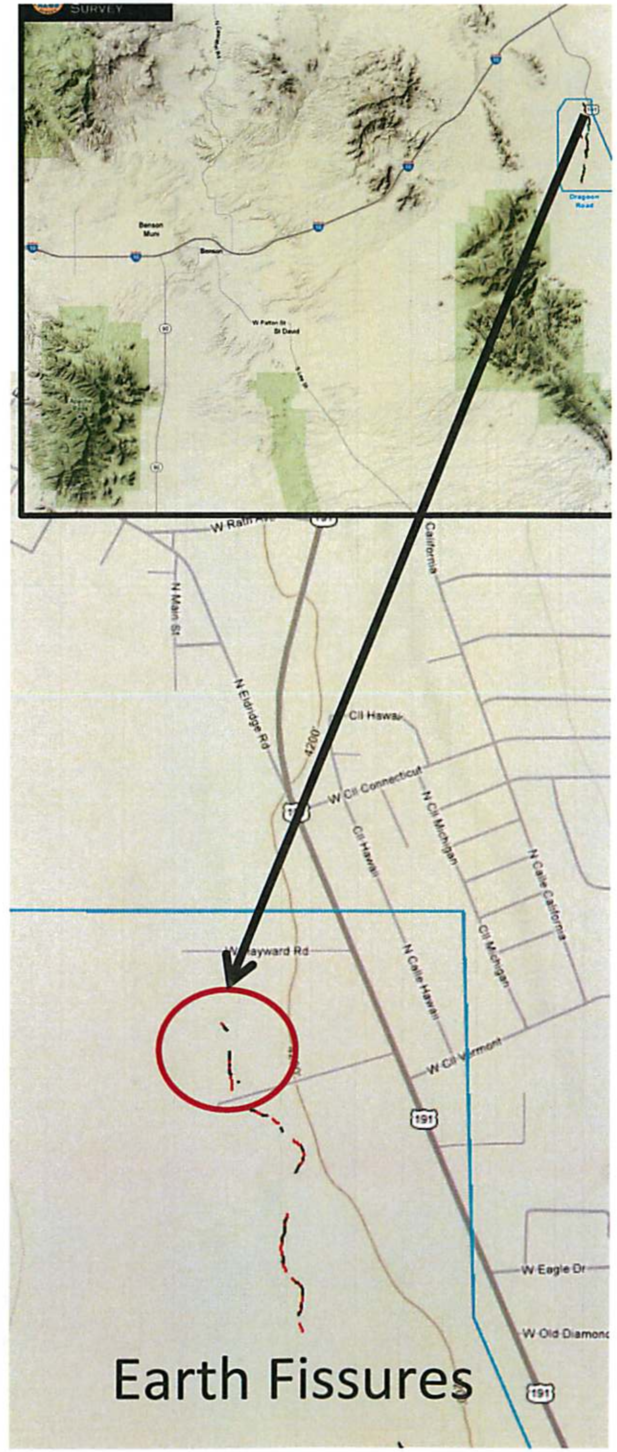


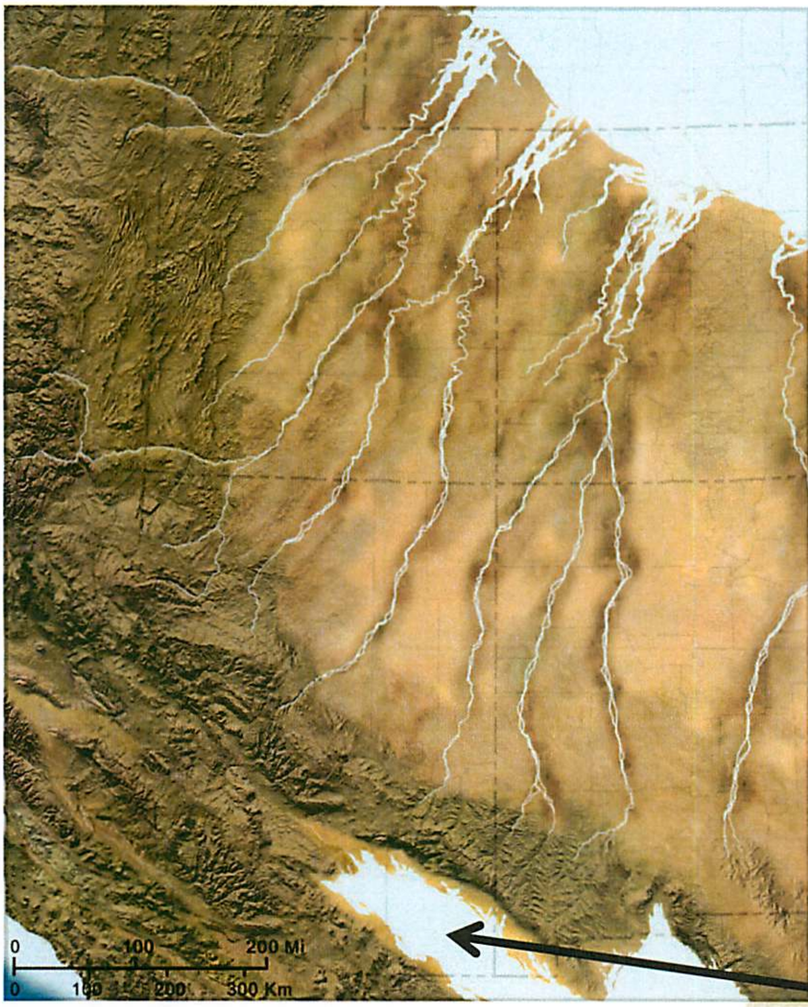


Saint David Formation



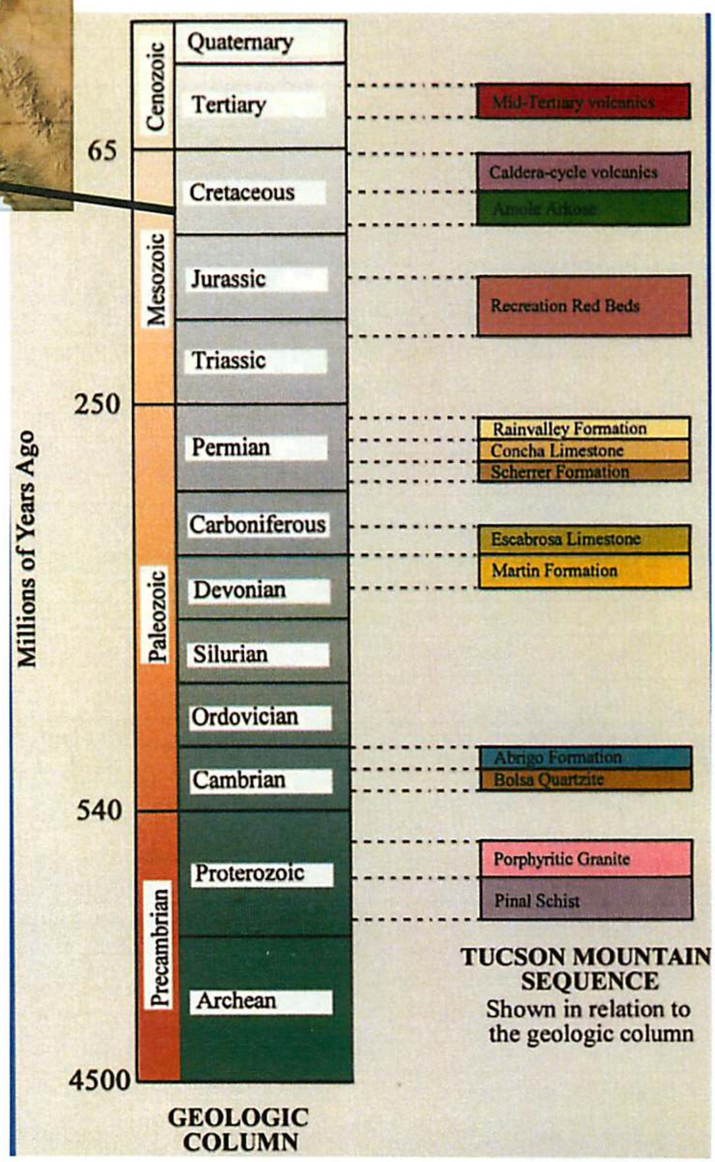
Earth Fissures

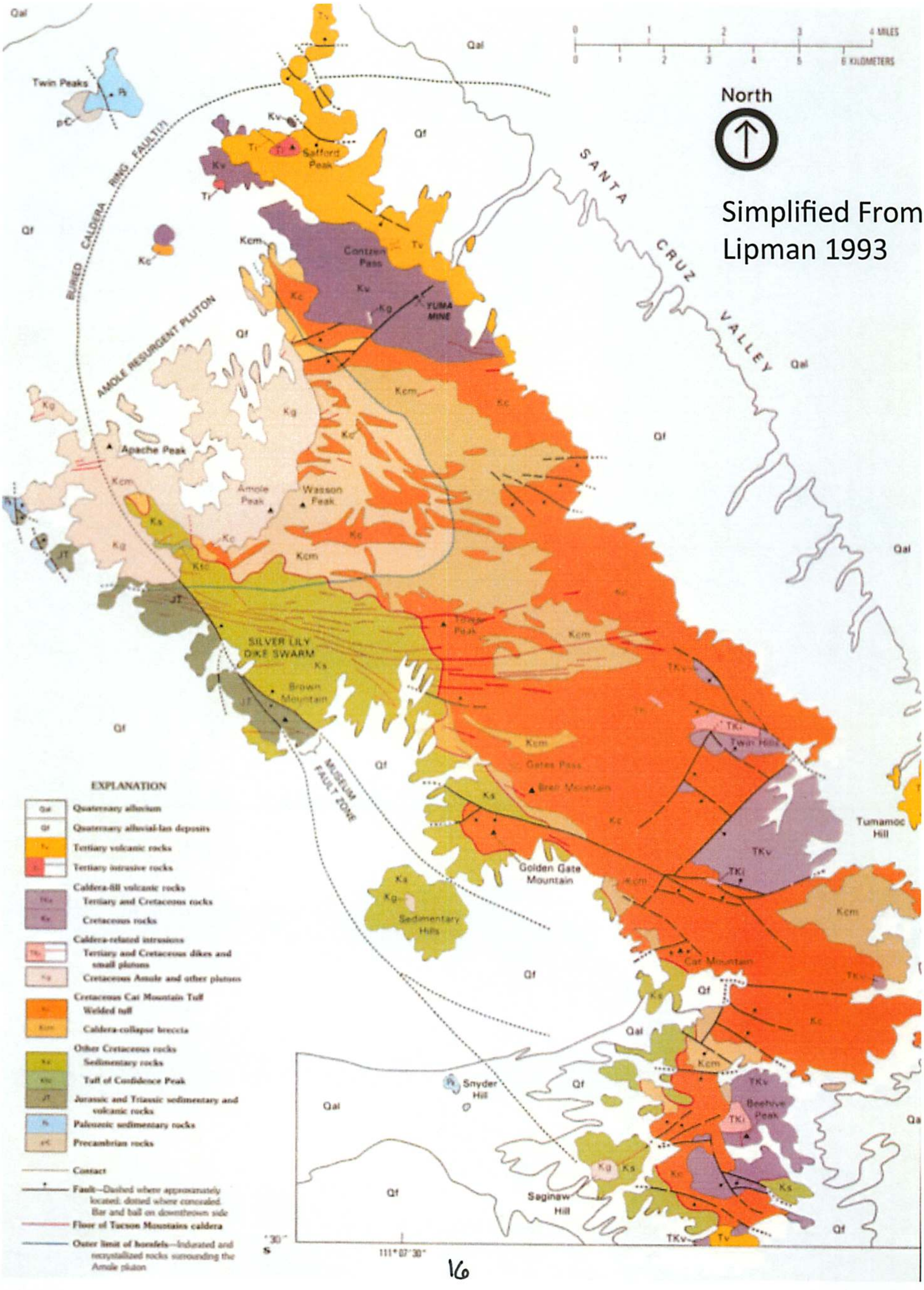


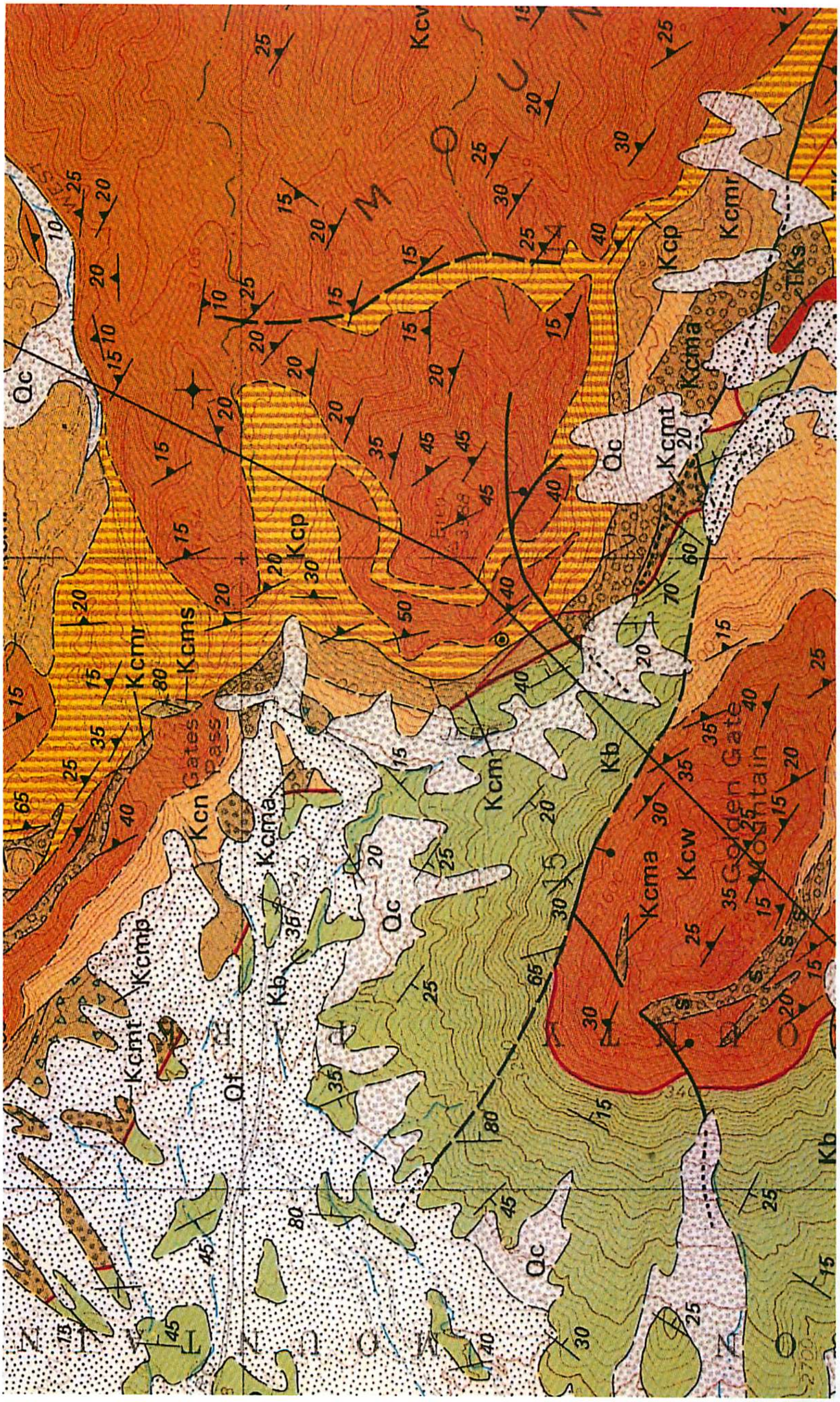


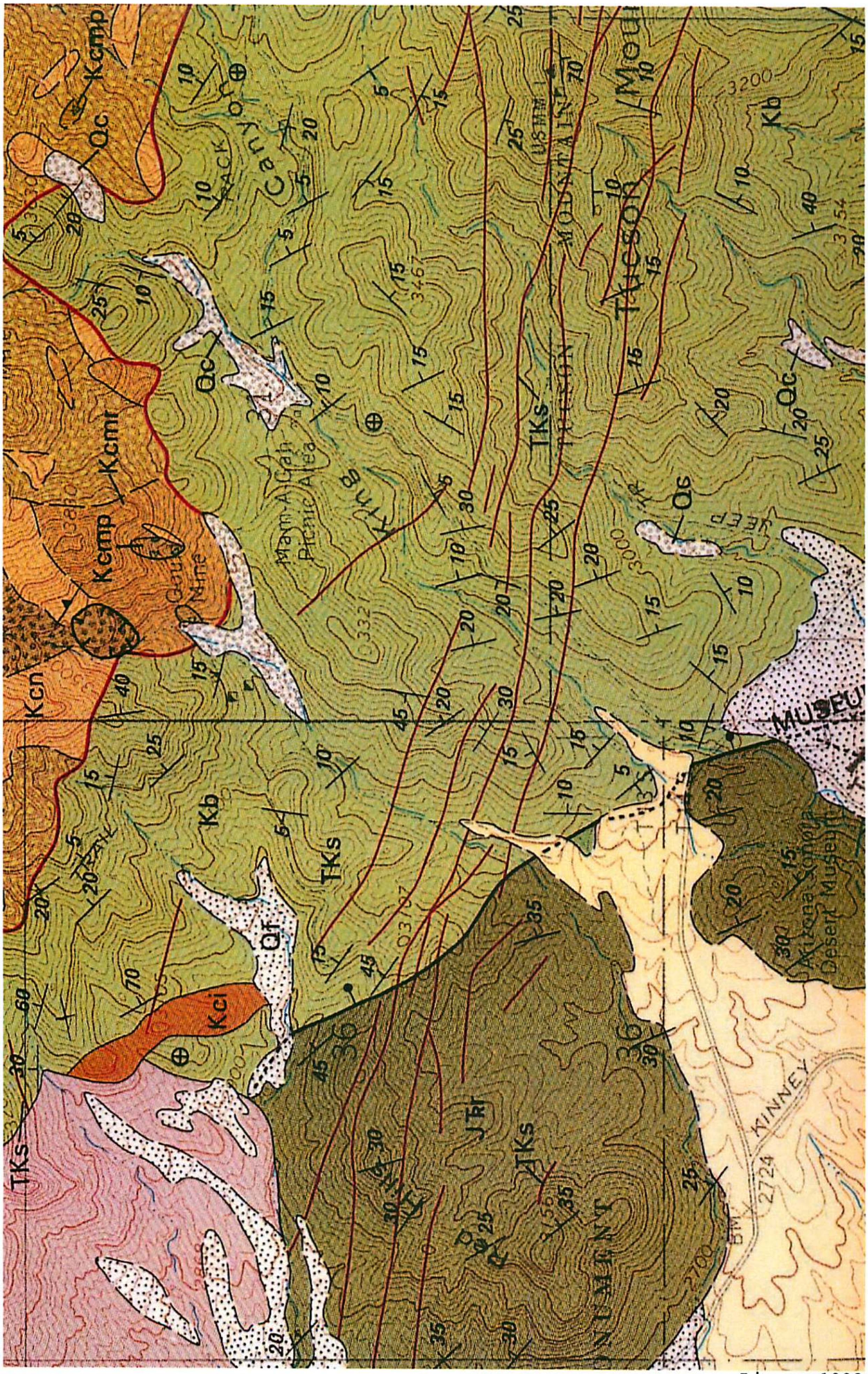
Early Cretaceous Ron Blakey

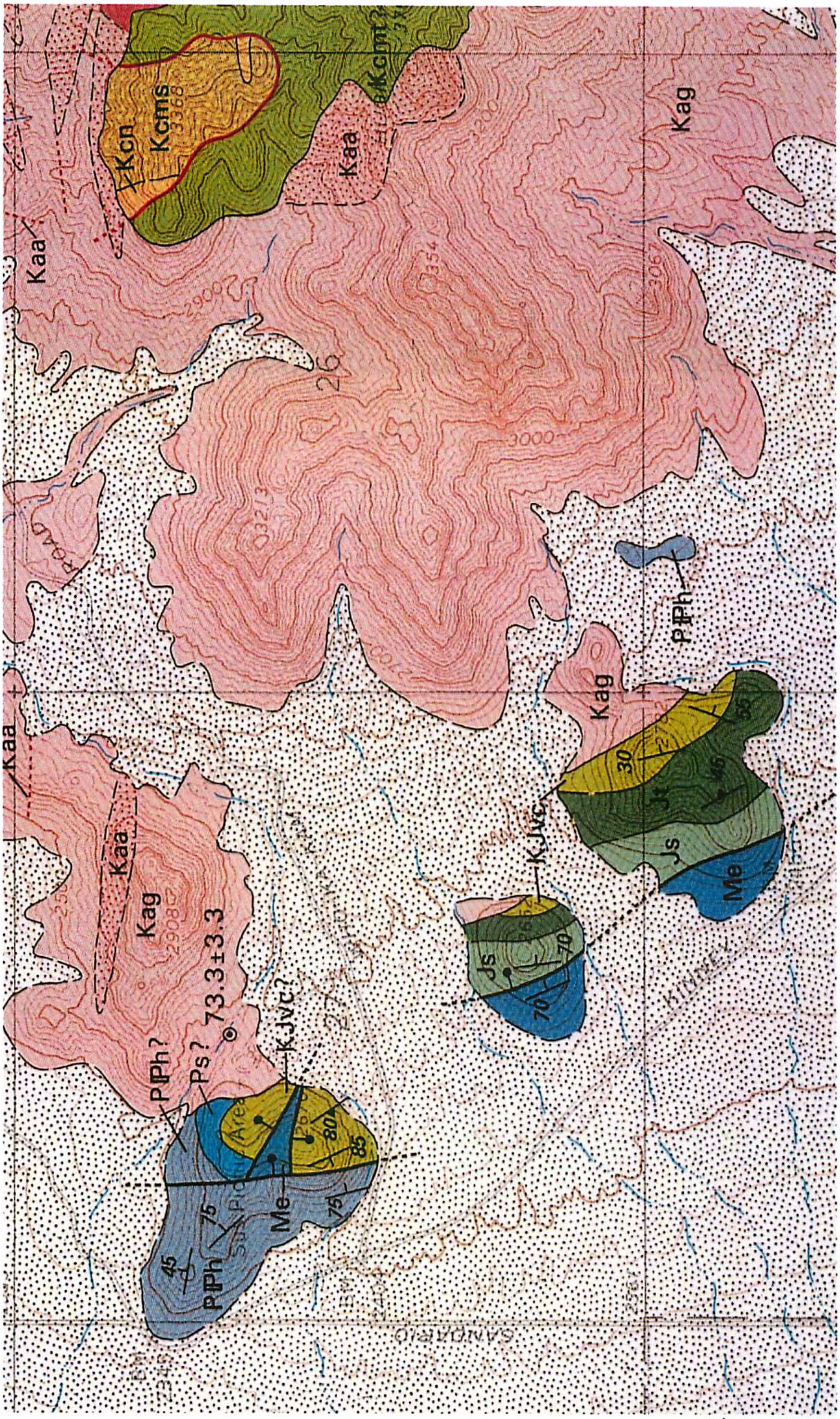
Local Strata from Kring, 2002




North
Simplified From Lipman 1993
0 1 2 3 4 MILES
0 1 2 3 4 5 6 KILOMETERS
Twin Peaks
BURIED CALDERA RING FAULT(?)
AMOLE RESURGENT PLUTON
Safford Peak
Contzen Pass
YUMA MINE
SANTA CRUZ VALLEY
Apache Peak
Amole Peak
Wasson Peak
SILVER LILY DIKE SWARM
Brown Mountain
MUSEUM FAULT ZONE
Gates Pass
Bren Mountain
Twin Hills
Golden Gate Mountain
Sedimentary Hills
Tumamoc Hill
Cat Mountain
Snyder Hill
Beehive Peak
Saginaw Hill
111° 07' 30"
EXPLANATION
Quaternary alluvium
Quaternary alluvial-fan deposits
Tertiary volcanic rocks
Tertiary intrusive rocks
Caldera-fill volcanic rocks
Tertiary and Cretaceous rocks
Cretaceous rocks
Caldera-related intrusions
Tertiary and Cretaceous dikes and small plutons
Cretaceous Amole and other plutons
Cretaceous Cat Mountain Tuff
Welded tuff
Caldera-collapse breccia
Other Cretaceous rocks
Sedimentary rocks
Tuff of Confidence Peak
Jurassic and Triassic sedimentary and volcanic rocks
Paleozoic sedimentary rocks
Precambrian rocks
Contact
Fault—Dashed where approximately located; dotted where concealed. Bar and ball on downthrown side
Floor of Tucson Mountains caldera
Outer limit of hornfels—Indurated and recrystallized rocks surrounding the Amole pluton


Golden Gate Mountain
Gates Pass
Kcw
Kcma
Kcp
Kcmr
Kcms
Kcn
Kcmp
Kcmt
Kcm
Kb
Qc
Qf
TKs


Kcmp
Qc
Kcmr
Kcn
Kb
TKs
Qf
Kci
JTr
Mam-A-Gah Picnic Area
TUCSON
MOUNTAINS
MUSEUM
Arizona-Sonora Desert Museum
KINNEY
JEEP


Kcn
Kcms
Kaa
Kag
Kaa
Kaa
Kag
73.3±3.3
KJvc?
PIPh?
Ps?
Me
PIPh
45
75
75
80
85
Js
70
70
KJvc
Kag
30
46
55
Js
Me
PIPh
3000
2900

Lipman 1993

Common Rock Forming Minerals

Dark-Colored minerals			
Hardness	**Cleavage**	**Physical Properties**	**Name**
Hardness >5	Excellent or good	Dark gray, Blue-gray or black. May be iridescent. Cleavage in 2 planes at nearly right angles, Striations. Hardness-6	**Plagioclase Feldspar**
		Brown, gray, green or red. Cleavage in 2 planes at nearly right angles. Exsolution Lamellae. Hardness-6	**Potassium Feldspar**
		Opaque black. 2 cleavage planes at 60°and 120°. Hardness- 5.5	**Hornblende (Amphibole)**
	Poor or absent	Opaque red, gray, hexagonal prisms with striated flat ends. Hardness- 9	**Corrundum**
		Gray, brown or purple. Greasy luster. Massive or hexagonal prisms and pyramids. Transparent or translucent. Hardness- 7	**Quartz Black or brown- Smoky , Purple- Amethyst**
		Opaque red or brown. Waxy luster. Hardness- 7. Conchoidal Fracture	**Jasper**
		Opaque black. Waxy luster. Hardness- 7	**Flint**
		Transparent- translucent dark red to black. Hardness- 7	**Garnet**
Hardness < 5	Excellent or good	Colorless, purple, green, yellow, blue. Octahedral cleavage. Hardness- 4	**Flourite**
		Green. Splits along 1 excellent cleavage plane. Hardness- 2-3	**Chlorite**
		Black to dark brown. Splits along 1 excellent cleavage plane. Hardness- 2.5-3	**Biotite mica**
	Poor or absent	Opaque green, yellow or gray. Silky or greasy luster. Hardness- 2-5	**Serpentine**
		Opaque white, gray or green. Can be scratched with fingernail. Soapy feel. Hardness- 1	**Talc**
		Opaque earthy red to light brown. Hardness- 1.5-6	**Hematite**

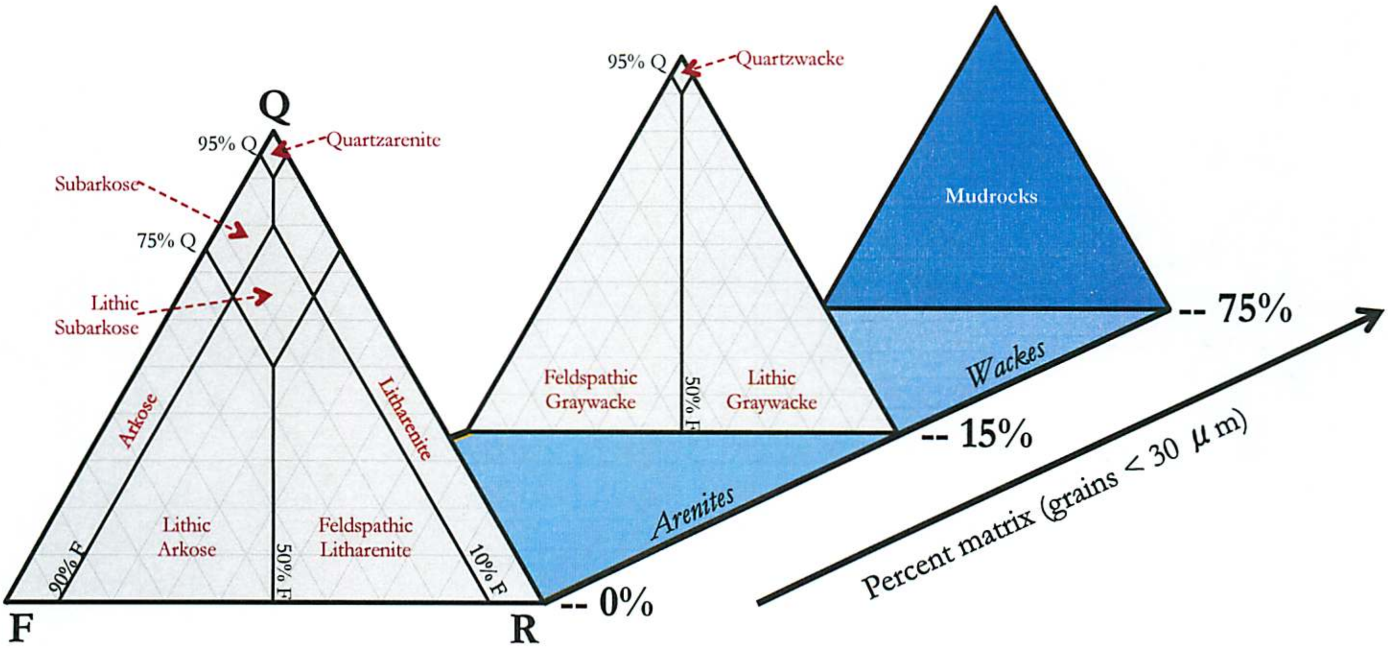
Light-colored minerals			
Hardness	**Cleavage**	**Physical Properties**	**Name**
Hardness >5	Excellent or good	White or gray. Cleavage in 2 planes at nearly right angles, Striations. Hardness-6	**Plagioclase Feldspar**
		Orange, brown, white, gray, green or pink. Cleavage in 2 planes at nearly right angles. Exsolution Lamellae. Hardness-6	**Potassium Feldspar**
		Pale brown, white or gray. Long slender prisms. Cleavage in 1 plane. Hardness- 6-7	**Sillimanite**
	Poor or absent	Opaque red, gray, white hexagonal prisms with striated flat ends. Hardness- 9	**Corrundum**
		Colorless, white, gray or other colors. Greasy luster. Massive or hexagonal prisms and pyramids. Transparent or translucent. Hardness- 7	**Quartz White-Milky, Yellow-Citrine, Pink- Rose**
		Opaque gray or white. Waxy luster. Hardness- 7. Conchoidal Fracture	**Chert**
		Colorless, white, yellow, light brown. Translucent opaque. Laminated or massive. Cryptocrystalline. Hardness- 7	**Chalcedony**
		Pale olive green. Conchoidal fracture. Transparent or translucent. Hardness- 7	**Olivine**
Hardness < 5	Excellent or good	Colorless, white, yellow, blue, green. Excellent cleavage in 3 planes. Breaks into rhombohedrons. Effervesces in HCl. Hardness- 3	**Calcite**
		Colorless, white, yellow, blue, green. Excellent cleavage in 3 planes. Breaks into rhombohedrons. Effervesces in HCl only if powdered. Hardness- 3.5-4	**Dolomite**
		White with tints of brown. Short tabular crystals or roses. Very heavy. Hardness- 3-3.5	**Barite**
		Colorless, white or gray. Massive or tabular crystals, blades or needles. Can be scratched by fingernail. Hardness- 2	**Gypsum**
		Colorless, white. Cubic crystals. Salty taste. Hardness- 2.5	**Halite**
		Colorless, purple, green, yellow, blue. Octahedral cleavage. Hardness- 4	**Flourite**
		Colorless, yellow, brown. Splits along 1 excellent cleavage plane. Hardness- 2-2.5	**Muscovite mica**
	Poor or absent	Yellow crystals or earthy masses. Hardness 1.5-2.5	**Sulfur**
		Opaque green, yellow or gray. Silky or greasy luster. Hardness- 2-5	**Sepentine**
		Opaque white, gray or green. Can be scratched with fingernail. Soapy feel. Hardness- 1	**Talc**
		Opaque earthy white to light brown. Hardness- 1-2	**Kaolinite**

Metallic			
	Streak	**Physical Properties**	**Name**
Hardness > 5	Dark Gray	Brass yellow	**Pyrite**
		Dark gray-black, attracted to magnet	**Magnetite**
	Brown	Silvery black to black tarnishes gray	**Chromite**
Harness < 5	Red-Red/Brown	Silvery gray, black, or brick red	**Hematite**
	Dark Gray	Brass yellow, tarnishes dark brown or purple	**Chalcopyrite**
		Iridescent blue, purple or copper red, tarnishes dark purple	**Bornite**
		Silvery gray, tarnishes dull gray Cleavage good to excellent	**Galena**
		Dark gray to black, can be scratched with fingernail	**Graphite**

Sedimentary Rocks

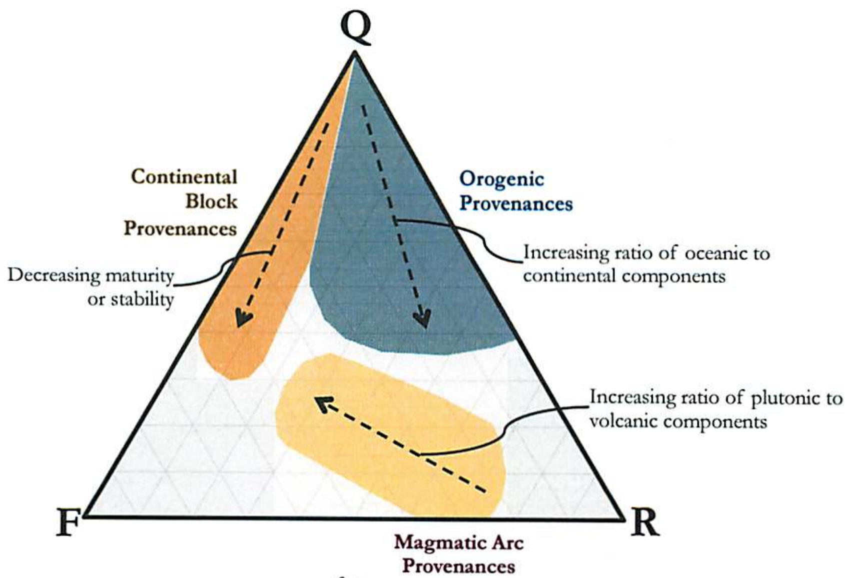
McBride, 1963 & Dott, 1964 Classification Scheme for Clastic Sedimentary Rocks

Scheme based on the normalized percentages of the visible grains: quartz and chert(Q), feldspar (F), and lithic rock fragments (R) – as well as the percent composed of matrix (mud & silt)



Tectonic Setting for Clastic Sedimentary Rocks

Scheme based on the normalized percentages of the visible grains: quartz and chert(Q), feldspar (F), and lithic rock fragments (R) – as well as the percent composed of matrix (mud & silt). Regions based upon field data.



Sedimentary Rocks

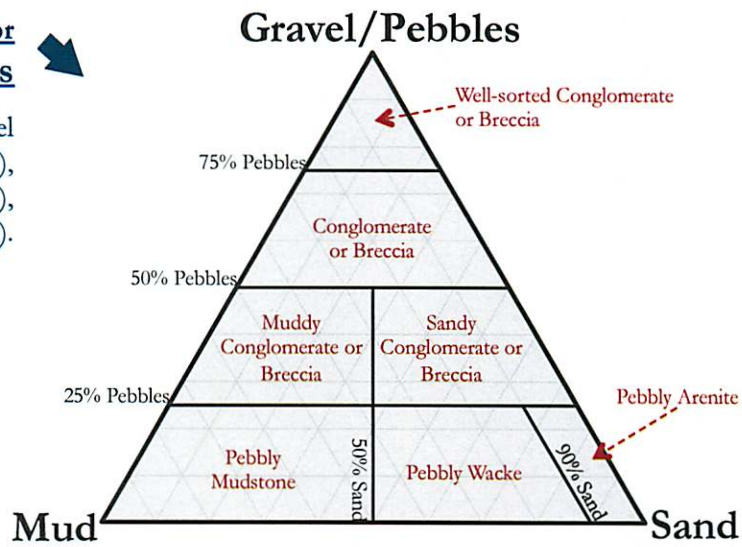
	Mudrocks (containing > 50% mud)			Rocks with <50%mud
	Silt dominant (> 2/3 of rock)	Clay and Silt	Clay dominant (> 2/3 of rock)	Sand-sized or larger grains dominant
Non-laminated	Siltstone	Mudstone	Claystone	Conglomerates, Breccias, Sandstones, etc.
Laminated	Laminated Siltstone	Mudshale	Clayshale	

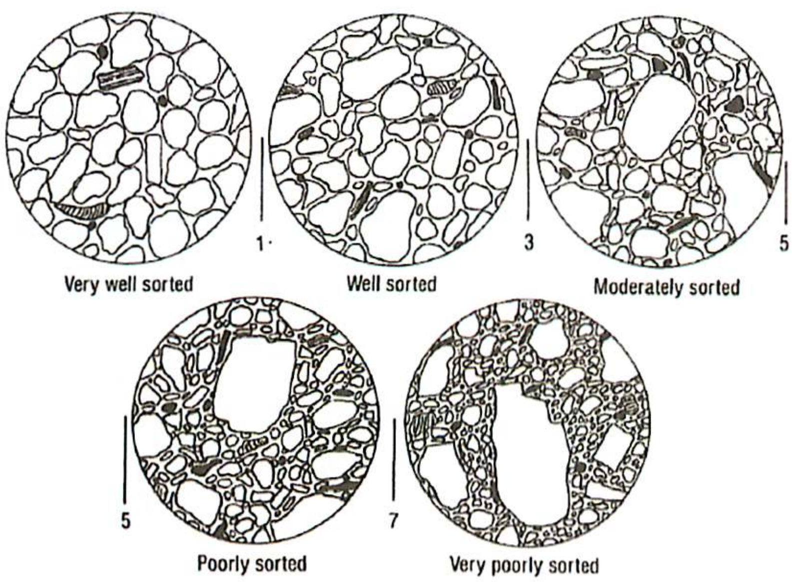
Classification Scheme for Mudrocks

Scheme based on clay/silt content, and whether the rock is laminated (layered) or not.

Classification Scheme for Sub-Conglomerates and Sub-Breccias

Scheme based on percent of a rock composed of: gravel or pebbles (size >2 mm), sand (2 mm > size > 1/16 mm), and mud (size < 1/16 mm).





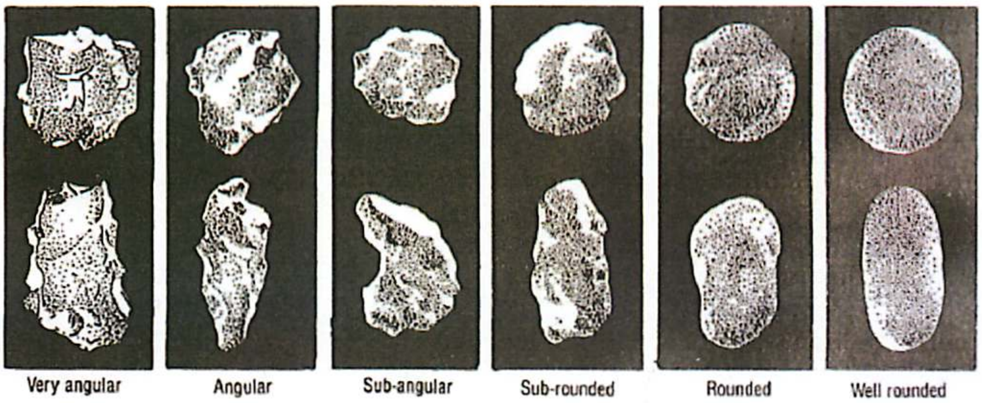
Estimating Sorting

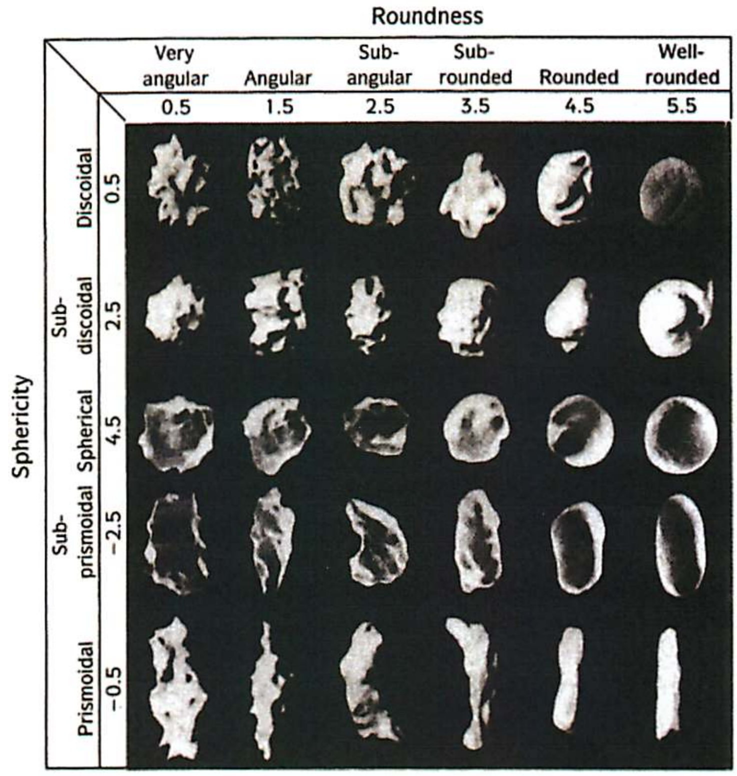
Example hand-lens view of detritus. From Compton, 1985

Sedimentary Rocks

Degrees of Rounding

Example hand-lens view of detritus of varying degrees of roundedness. The top row are equidimensional (spherical) grains, while the lower row are elongated grains. From Compton, 1985 and Davis & Reynolds, 1996, respectively.

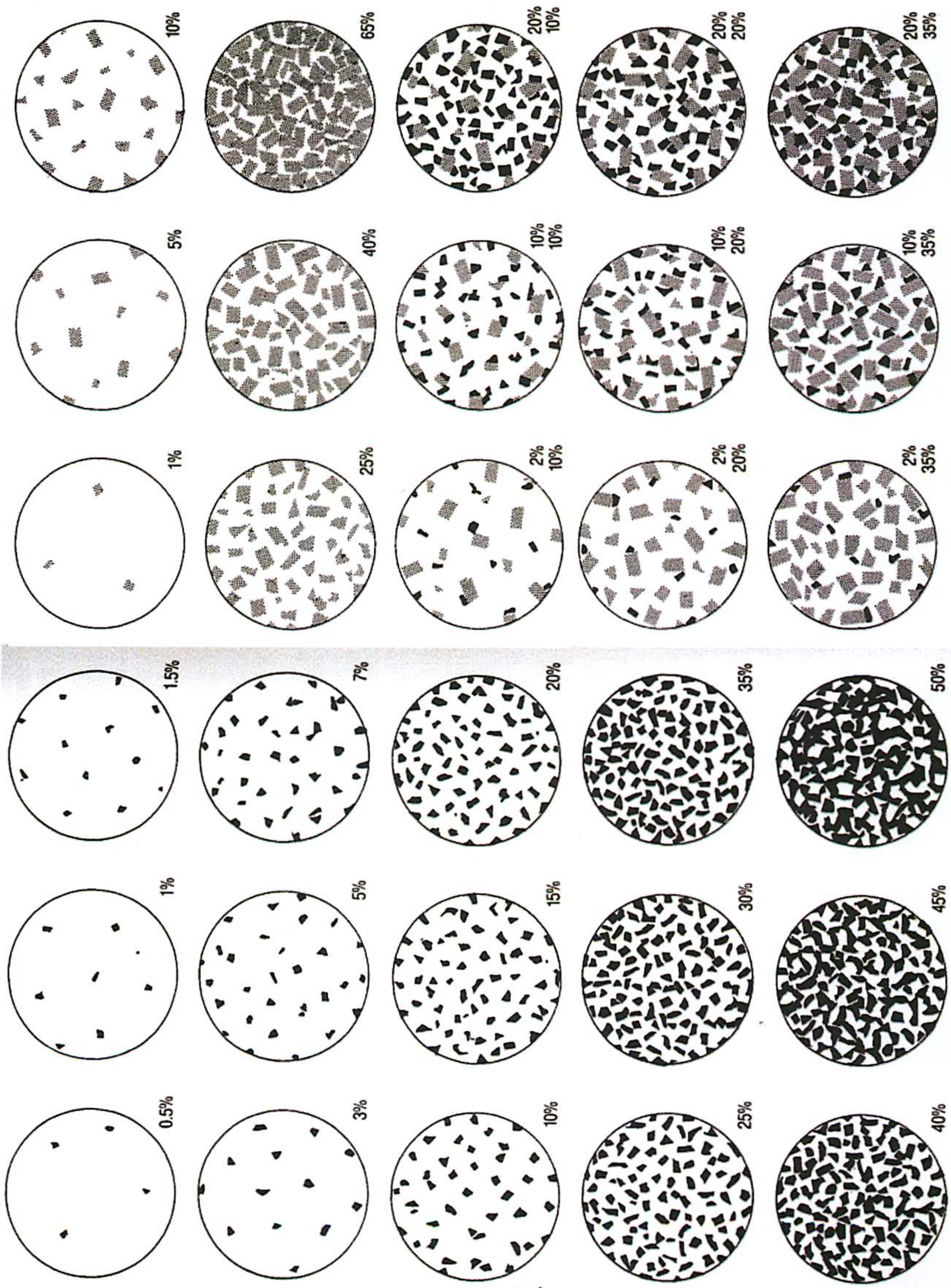




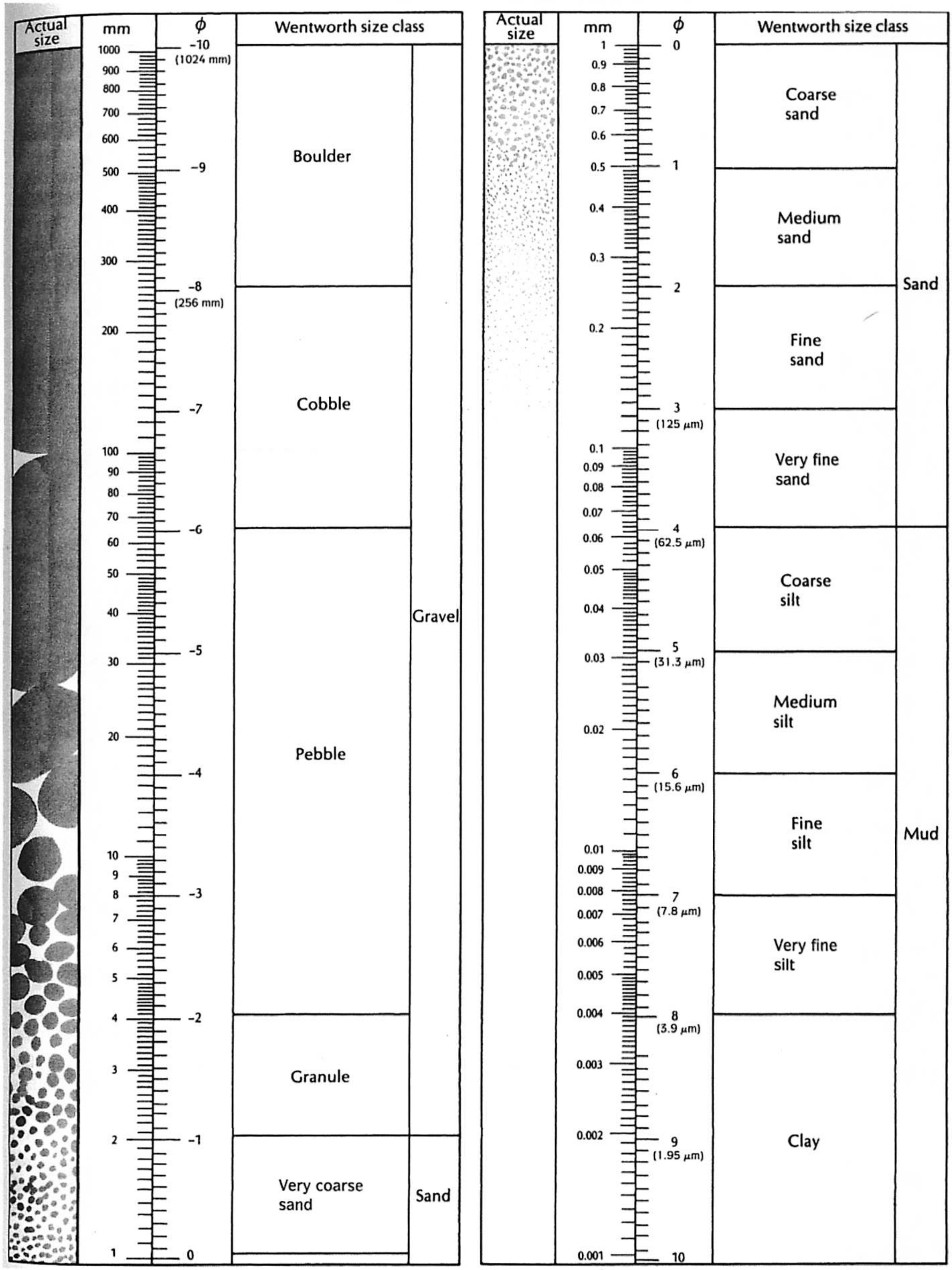
Sedimentary Rocks

Percentage Diagrams for Estimating Composition by Volume

Example hand-lens view of rocks with varying composition. To find weight percents, simply multiply each volume percent by the specific gravity of that mineral, and re-normalize. Compton, 1985



Sedimentary Rocks

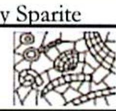
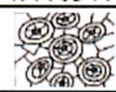
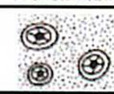
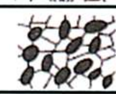


From Prothero and Schwab, 2004

Sedimentary Rocks: Carbonates

Folk Classification Scheme for Carbonate Rocks

Folk's classification scheme is based upon the composition (and type of allochems) within a limestone. Figures from Prothero and Schwab, 2004

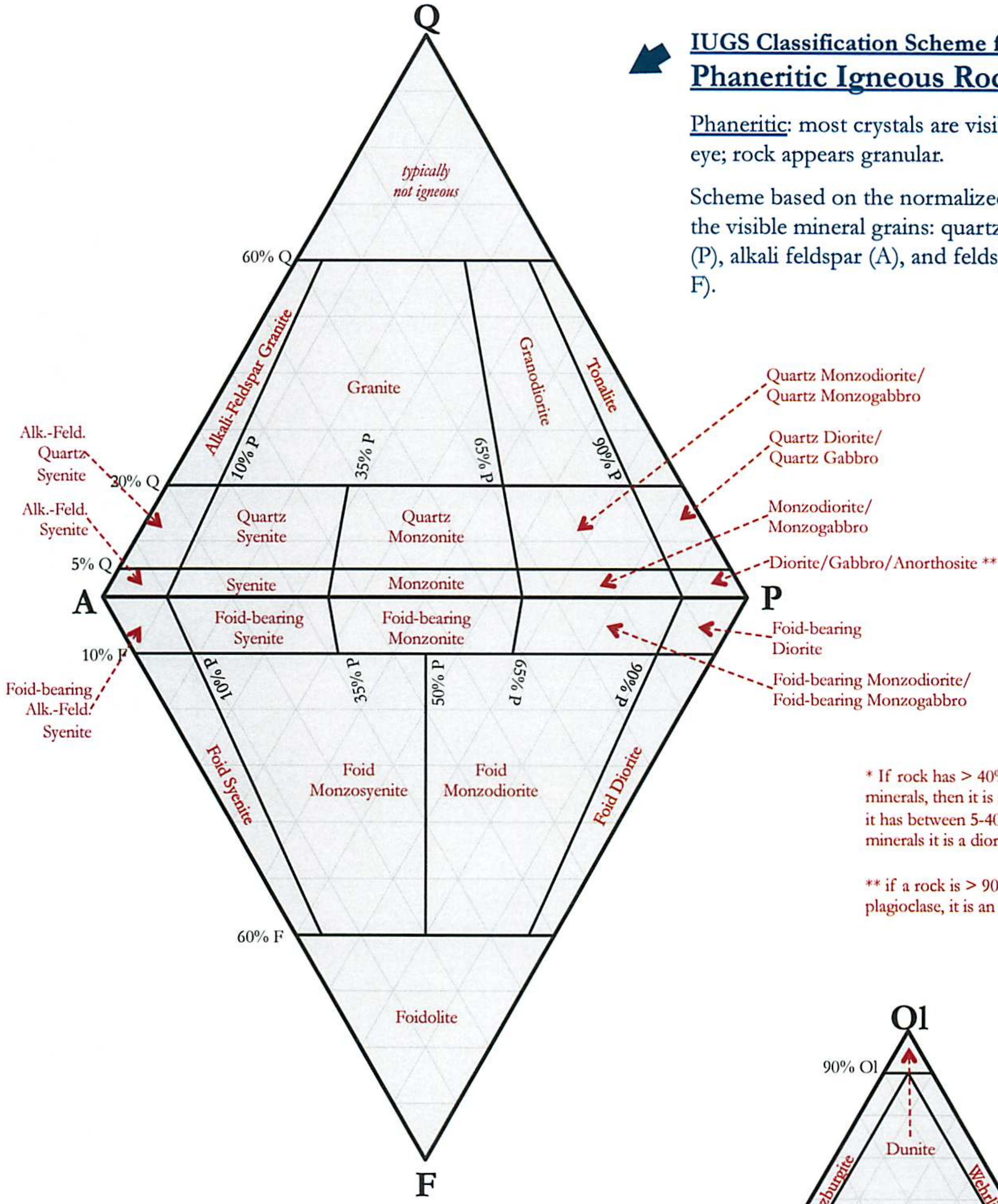
Principle Allochems in Limestone	Limestone Type			
	Cemented by Sparite		Cemented by Micritic Matrix	
Skeletal Grains (Bioclasts)	Biosparite		Biomicrite	
Ooids	Oosparite		Oomicrite	
Peloids	Pelsparite		Pelmicrite	
Intraclasts	Intrasparite		Intramicrite	
Limestone formed in place	Biolithite		Terrestrial Limestone	

Dunham Classification Scheme for Carbonate Rocks

Dunham's classification scheme is based upon depositional textures within a limestone.

Allochthonous Limestone (original components not organically bound during deposition)						**Autochthonous Limestone** (original components organically bound during deposition; reef rocks)		
Of the allochems, less than 10% are larger than 2 mm				Of the allochems, greater than 10% are larger than 2 mm				
Contains carbonate mud			No mud	Matrix supported	Grain supported	Organisms acted as baffles	Organisms are encrusting and binding	Organisms building a rigid framework
Grain supported		Grain supported						
Less than 10% grains	More than 10% grains							
Mudstone	Wackestone	Packstone	Grainstone	Floatstone	Rudstone	Bafflestone	Bindstone	Framestone

Igneous Rocks



IUGS Classification Scheme for
Phaneritic Igneous Rocks

Phaneritic: most crystals are visible to the naked eye; rock appears granular.

Scheme based on the normalized percentages of the visible mineral grains: quartz (Q), plagioclase (P), alkali feldspar (A), and feldspathoids (foids, F).

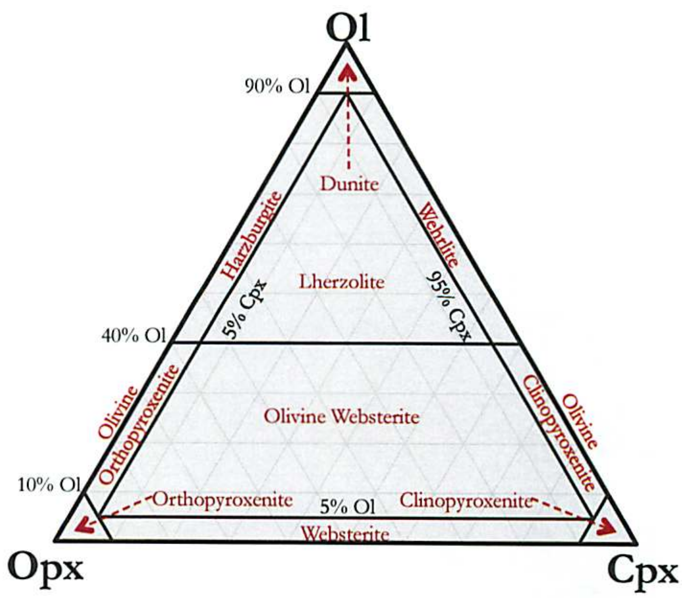
* If rock has > 40% mafic minerals, then it is a gabbo. If it has between 5-40% mafic minerals it is a diorite.

** if a rock is > 90% plagioclase, it is an anorthosite

IUGS Classification Scheme for
Phaneritic Ultramafic Igneous Rocks (1)

Ultramafic: more than 90% of the total minerals are mafic.

Scheme based on the normalized percentages of the visible minerals: olivine (Ol), orthopyroxene (Opx), and clinopyroxene (Cpx).

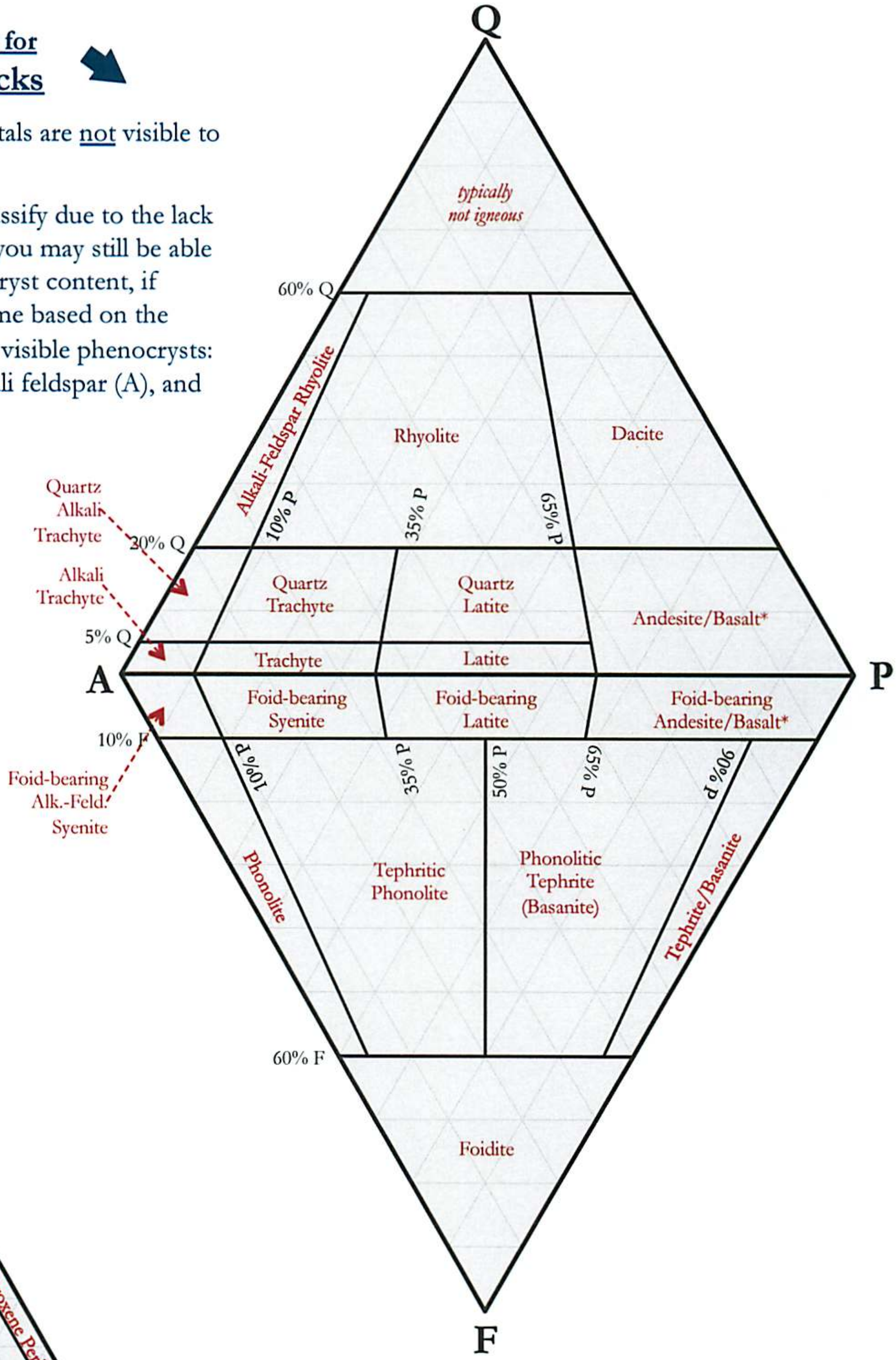


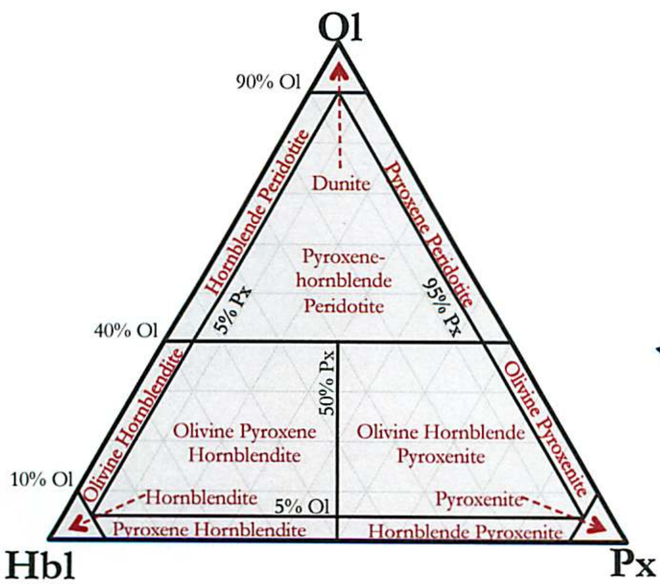
Igneous Rocks

IUGS Classification Scheme for Aphanitic Igneous Rocks

Aphanitic: the majority of crystals are not visible to the naked eye.

Aphanetic rocks are hard to classify due to the lack of visible minerals. However, you may still be able identify them based on phenocryst content, if phenocrysts are present. Scheme based on the normalized percentages of the visible phenocrysts: quartz (Q), plagioclase (P), alkali feldspar (A), and feldspathoids (foids, F).





IUGS Classification Scheme for Phaneritic Ultramafic Igneous Rocks (2)

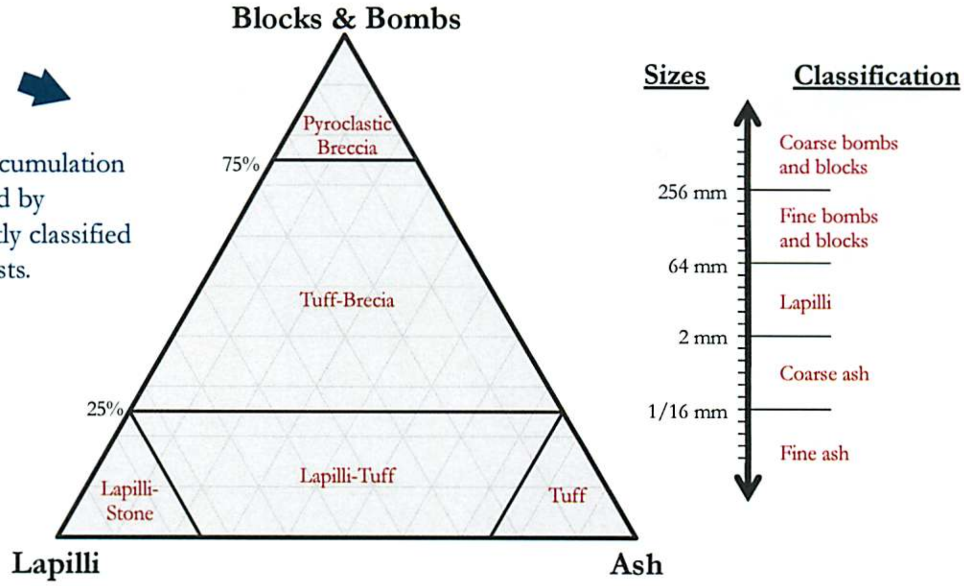
Ultramafic: more than 90% of the total minerals are mafic.

Scheme based on the normalized percentages of the visible minerals: olivine (Ol), hornblende (Hbl), and pyroxene (Px).

Igneous Rocks

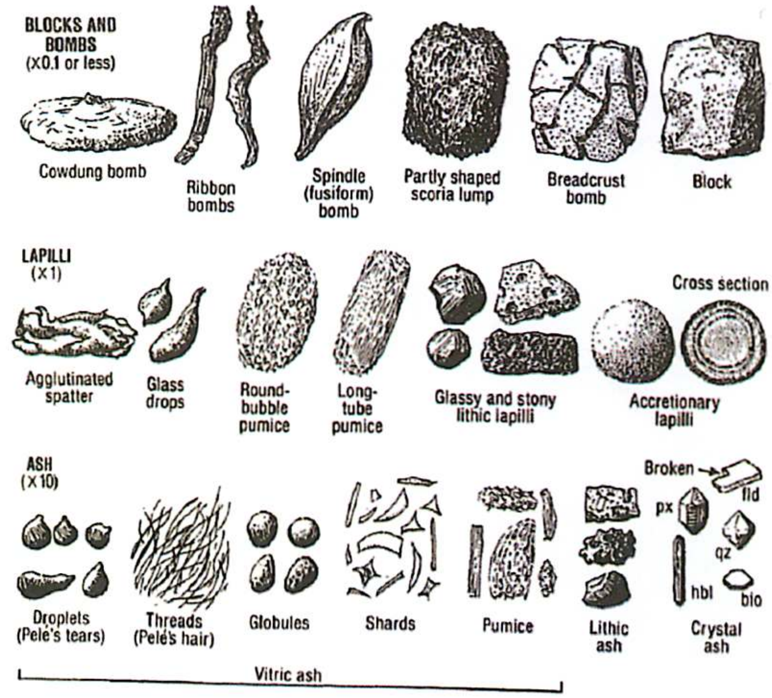
Classification Scheme for Pyroclastic Igneous Rocks

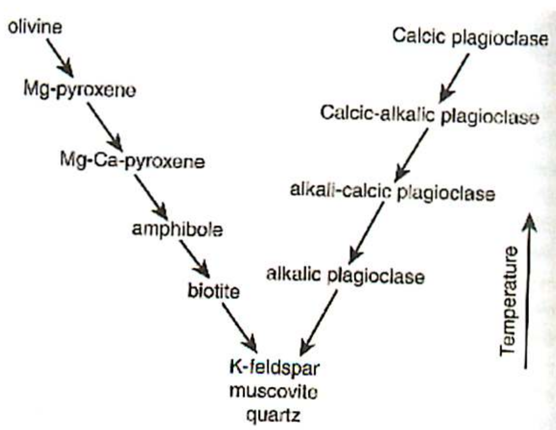
Pyroclastic rocks are formed via the accumulation of fragments of volcanic rock scattered by volcanic explosions. They are frequently classified based upon the size distribution of clasts.



Types of Tephra (Pyroclasts)

In each row, the viscosity of the lava increases to the right. From Compton, 1985.





Bowen's Reaction Series

From Winter, 2010.

Metamorphic Rocks

Classification Scheme for Metamorphic Rocks

Based upon texture and mineralogical composition.

Structure & Texture		Characteristic Properties	Characteristic Mineralogy	Rock Name
Foliate (layered)	Increasing grain size, and degree of metamorphism ↓	Dull luster; very flat fracture surface; grains are too small to readily see; more dense than shale	No visible minerals	Slate
		Silky sheen; Crenulated (wavy) fracture structure; A few grains visible, but most are not	Development of mica and/or hornblende possible	Phyllite
		Sub-parallel orientations of individual mineral grains; wavy-sheet like fracture; often contains porphyroblasts; thinly foliated	Abundant feldspar; Quartz and mica are common; hornblende possible	Schist
		Sub-parallel, alternating bands or layers of light and dark material; coarsely foliated; blocky fracture	Abundant feldspars; Quartz, mica, and hornblende are common	Gneiss
Foliate (layered)		Interlocking crystals; effervesces in dilute HCl; softer than glass	Calcite	Marble
		Nearly equigranular grains; fracture across grains (not around them); sub-vitreous appearance; smooth feel compared to sandstone	Quartz	Quartzite

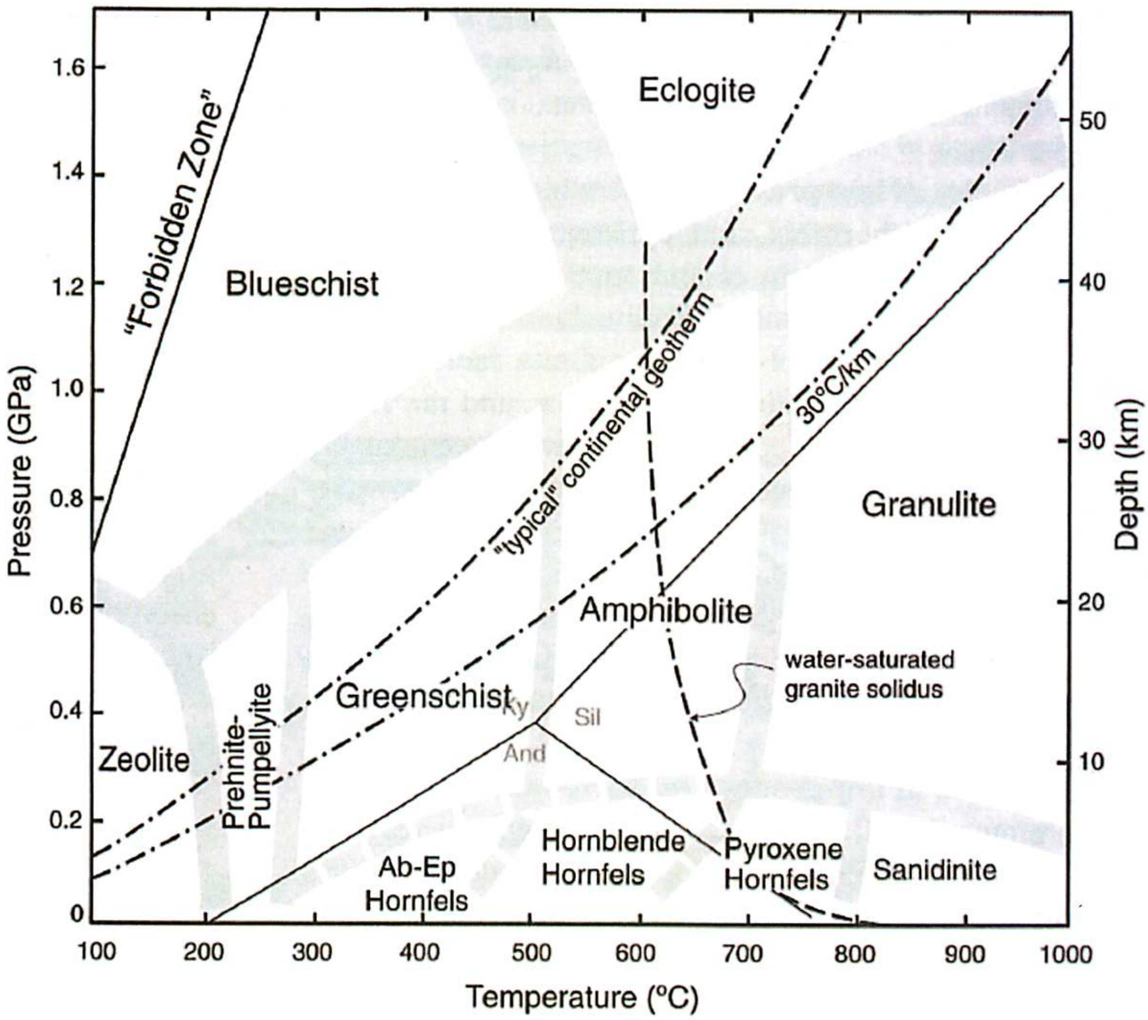
Mineralogy for Metamorphic Rock Facies

Facies	Definitive Mineral Assemblages in Mafic Rocks
Zeolite	zeolites: especially laumontite, wairakite, analcime (in place of other Ca-Al silicates such as prehnite, pumpellyite and epidote)
Prehnite-Pumpellyite	prehnite + pumpellyite (+ chlorite + albite)
Greenschist	chlorite + albite +epidote (or zoisite) + actinolite ± quartz
Amphibolite	hornblende + plagioclase (oligoclase, andesine) ± garnet
Granulite	orthopyroxene + clinopyroxene + plagioclase ± garnet
Blueschist	glaucophane + lawsonite or epidote/zoisite (± albite ± chlorite ± garnet)
Eclogite	pyralspite garnet + omphacitic pyroxene (± kyanite ± quartz), no plagioclase
Contact Facies	mineral assemblages in mafic rocks of the facies of contact metamorphism do not differ substantially from those of the corresponding regional facies at higher pressure

Metamorphic Rocks

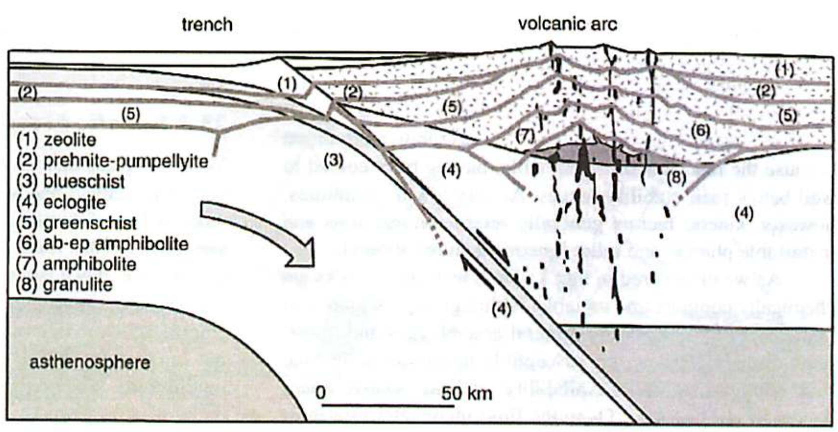
Metamorphic Rock Facies, P vs. T diagram

From Winter, 2010



Schematic of Island Arc, and the origins of Metamorphic Facies

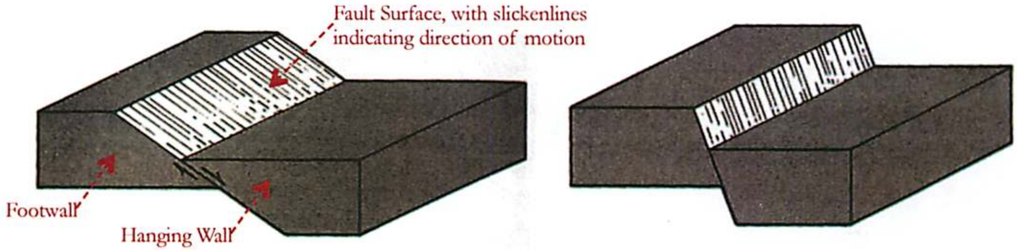
A schematic cross section of an island arc. Light gray lines are isotherms. From Winter, 2010



Structural Geology: Normal Faults

Normal Faults

In normal faults, the footwall goes up with respect to the hanging wall. Normal faults are indicative of extension. Figures from Davis & Reynolds, 1996.

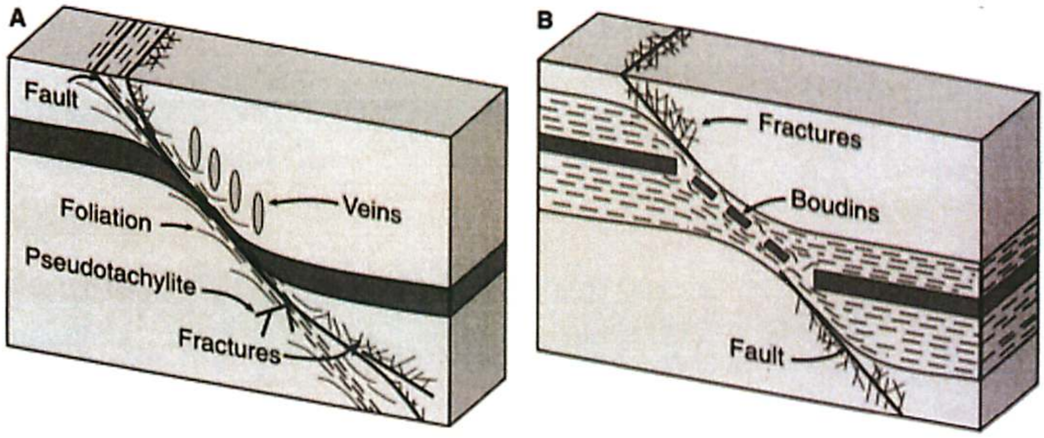


Low-angle Normal Slip Fault

Normal Slip Fault

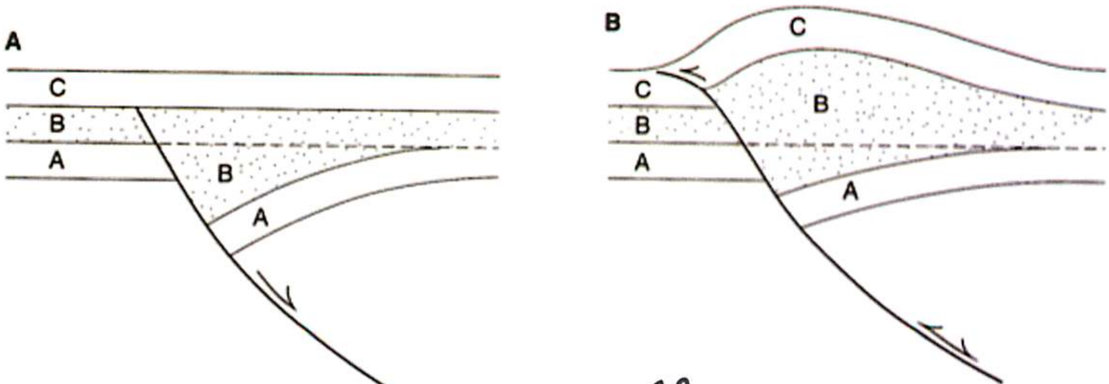
Effects of Brittle or Ductile Shear in Normal Faults

The block diagrams below illustrate the effects of changing the nature of deformation, between brittle deformation (which results in clear fault planes, fractures and fault rocks), ductile deformation (which causes deformation over a larger shear zone). Often, strata of different rheologies will behave differently, as is shown in the figure at right. The dashed layer was weak and deformed ductilely, while the middle grey layer was rigid and formed boudins. Figures from Davis & Reynolds, 1996.



Inversion Tectonics

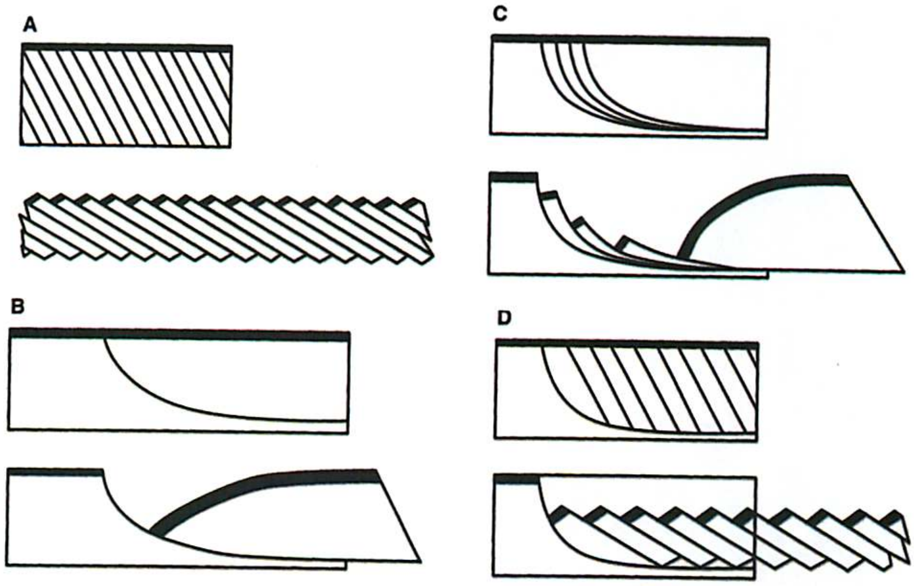
If the regional stresses change, previously inactive faults can reactivate, and change their sense of motion. In the figure at left, layer-A was formed prior to the formation of a normal fault. Layer-B and layer-C were deposited after the formation, and shut down of the fault. In the figure at the right, the fault has reactivated, though as a reverse fault. The resulting stratigraphic sequence is a combination of effects one would expect from both normal and reverse faults. Figures from Davis & Reynolds, 1996.

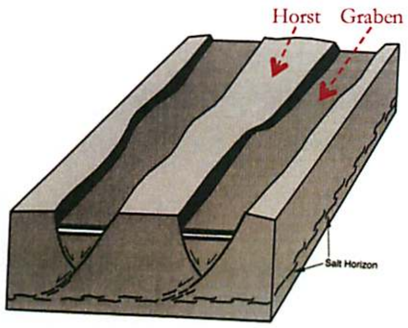


Structural Geology: Normal Faults

Normal Faults Geometries

Various normal fault geometries are possible. They all allow for lithospheric extension. (A) Domino style faulting. (B) Listric normal faulting with reverse drag. (C) Imbricate listric normal faulting. Note that listric faulting can cause extreme rotation of faulted blocks. (D) Listric normal faulting bounding a family of planar normal faults. Figures from Davis & Reynolds, 1996.



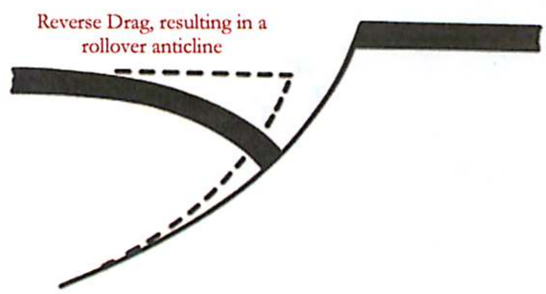


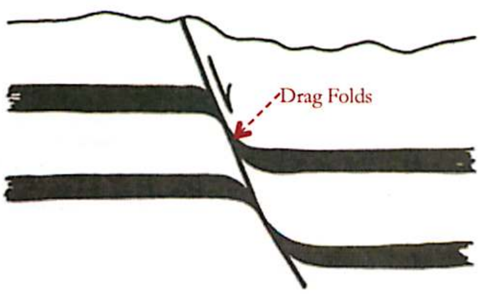
Horsts & Grabens

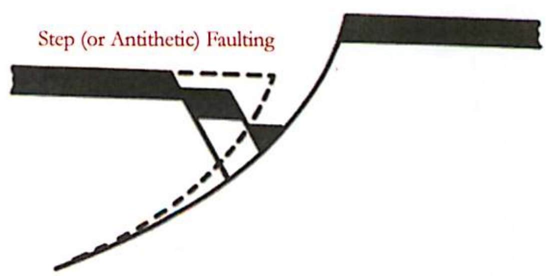
Classical formation describing fault-bounded uplifted (horsts) and down-dropped blocks (grabens). Figures from Davis & Reynolds, 1996.

Drag Folds, Reverse Drag, and Step Faulting

Faulting does not always produce clean displacement along the fault surface. Fault blocks are frequently folded or fractured, and the nature of these deformations are non-trivial. Figures from Davis & Reynolds, 1996.



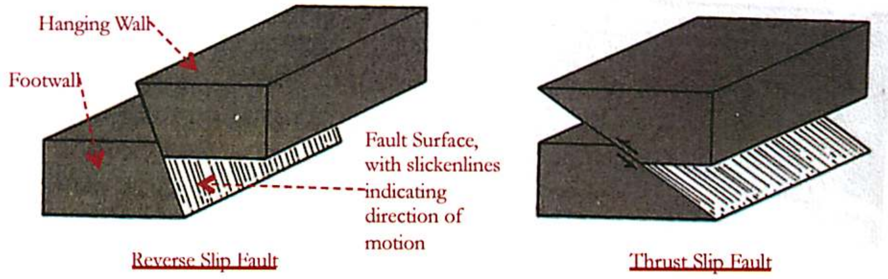




Structural Geology: Reverse & Thrust Faults

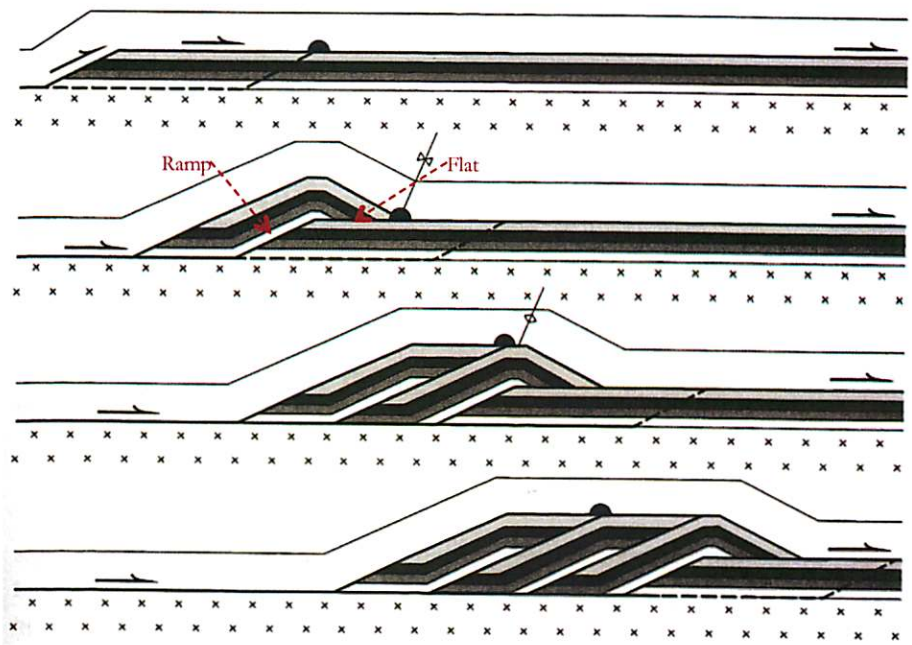
Reverse Faults

In reverse faults, the footwall goes down with respect to the hanging wall. Normal faults are indicative of compression. Thrust faults are reverse faults with fault dips <45 degrees. Figures from Davis & Reynolds, 1996.



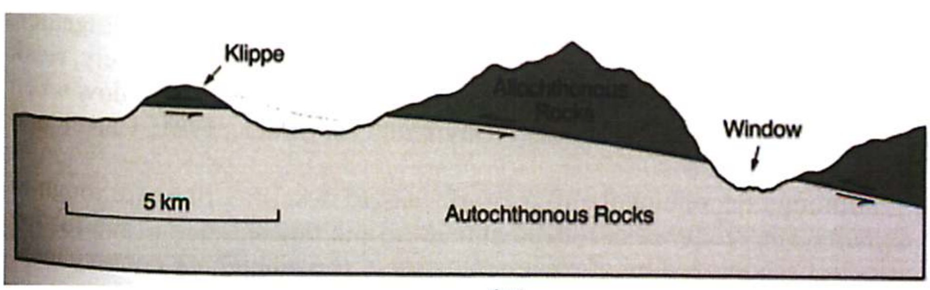
"Ramp-Flat" Geometry of Typical Thrust Fault Systems

In a regional thrust, faulted blocks are "thrust" on top of younger strata. The exact geometry of these thrust systems can vary significantly. Figures from Davis & Reynolds, 1996.

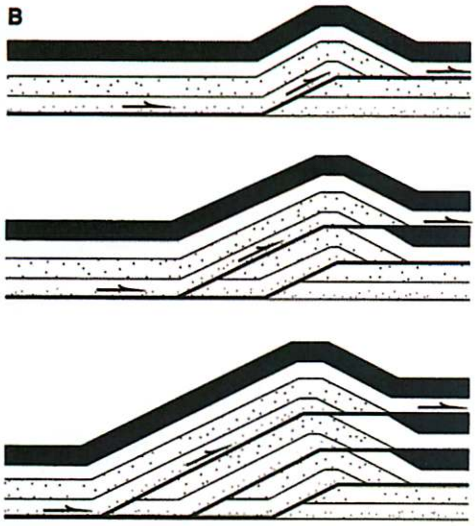


Klippe & Windows

Thrust faults move large blocks of non-indigenous rock (referred to as "allochthonous" rock) over emplaced rock (referred to as "autochthonous" rock). If the overlying allochthonous rock is eroded, it can create windows into the lower underlying autochthonous rock. Erosion can also create islands of isolated allochthonous rock, called klippe. Figures from Davis & Reynolds, 1996.



Structural Geology: Reverse & Thrust Faults

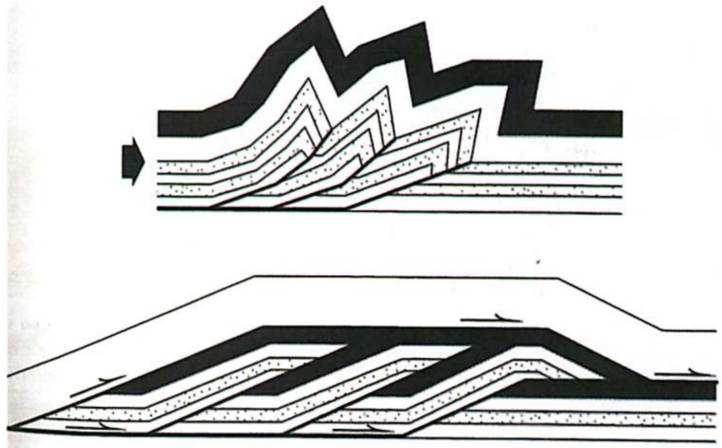


Out-of-Sequence Thrust Fault System

Unlike "in-sequence" thrust fault systems (as shown on the previous page, the "roof" of the thrust block in an out-of-sequence system becomes the "flat" for subsequent fault blocks. Figures from Davis & Reynolds, 1996.

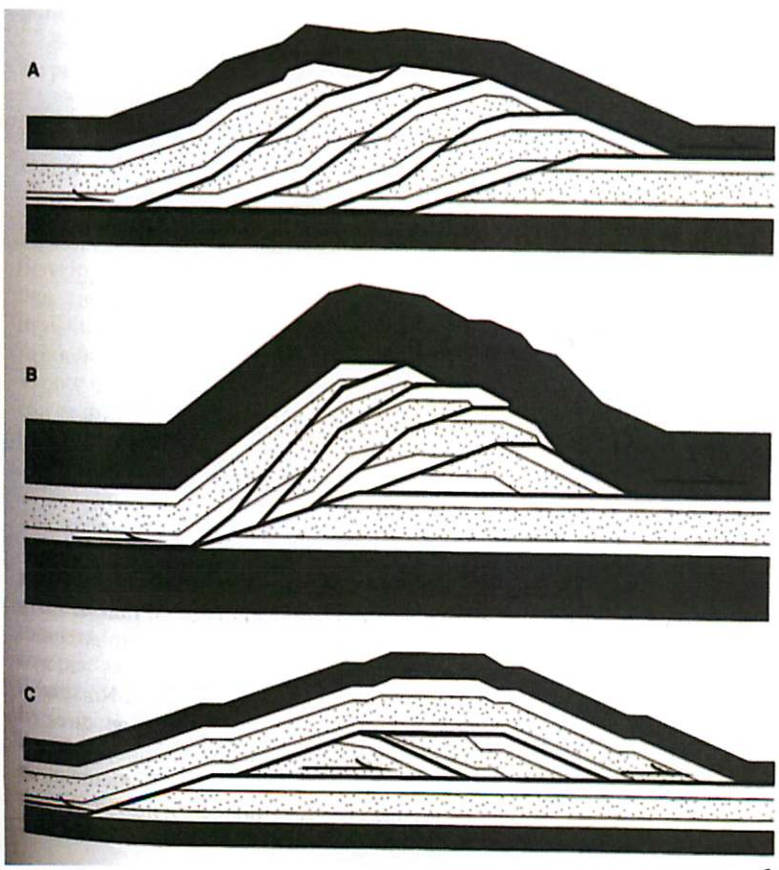
Imbricate Fans vs. Duplexes

Two thrust fault geometries: imbricate fans (top) and duplexes (bottom). Figures from Davis & Reynolds, 1996.



Forms of Duplexes

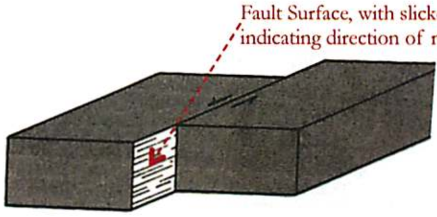
The exact form of a duplex or imbricate fan depends on the spacing of ramps and the amount of slip. (A) A normal duplex develops when slice length exceeds the fault slip. (B) An antiformal duplex develops when slice length and fault slip are effectively equal. (C) A forward-dipping duplex develops when the fault slip is greater than the slice length. Figures from Davis & Reynolds, 1996.



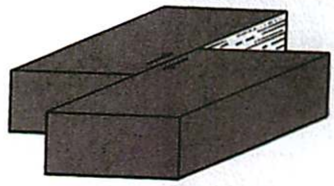
Structural Geology: Strike-Slip or Transform Faults

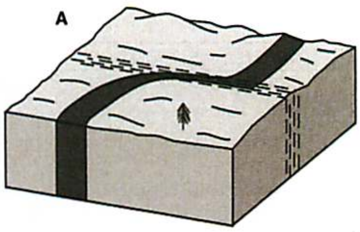
Strike-Slip Faults

In reverse faults, the footwall goes down with respect to the hanging wall. Normal faults are indicative of compression. Thrust faults are reverse faults with fault dips <45 degrees. Figures from Davis & Reynolds, 1996.

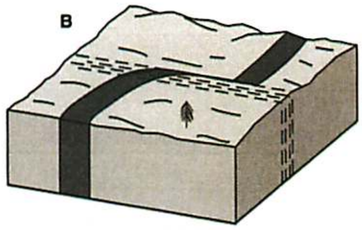


Left Lateral (Sinistral) Strike-Slip Fault


Right Lateral (Dextral) Strike-Slip Fault



Continuous Shear Zone



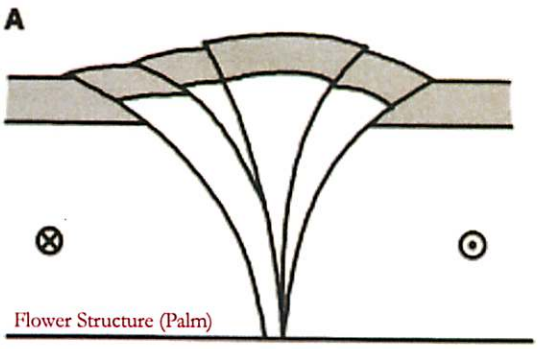
Discontinuous Shear Zone

Ductile Shear Zones

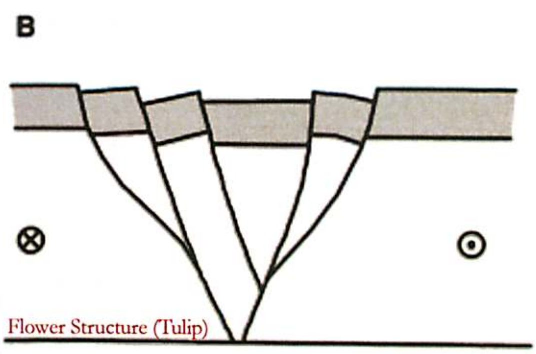
Shear in a strike-slip fault is not always located in a single plane. Sometimes, shear takes place over an extended region. Figures from Davis & Reynolds, 1996.

Brittle Shear Zones

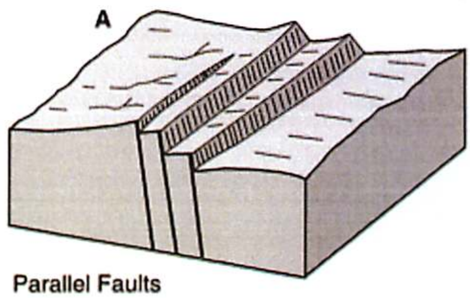
Figures from Davis & Reynolds, 1996.



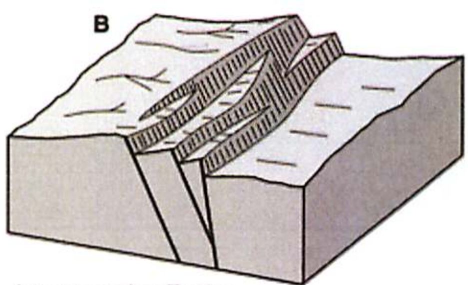
Flower Structure (Palm)



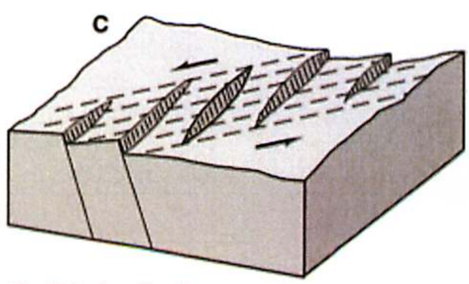
Flower Structure (Tulip)



Parallel Faults



Anastomosing Faults

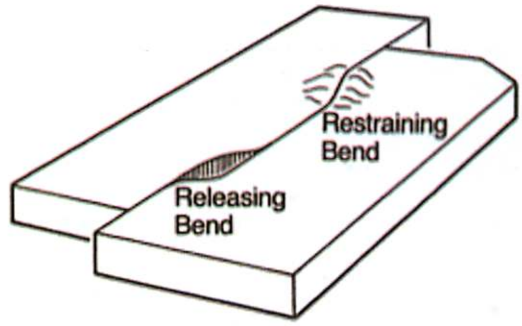


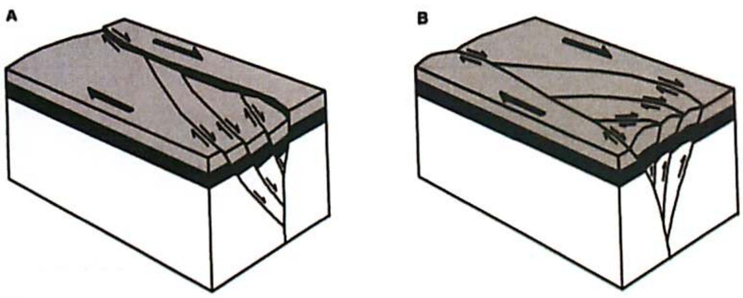
En Echelon Faults

Structural Geology: Strike-Slip or Transform Faults

Bends in Strike-Slip Faults

Strike-slip faults along irregularly curved faults creates localized regions of extension and compression. Figures from Davis & Reynolds, 1996.



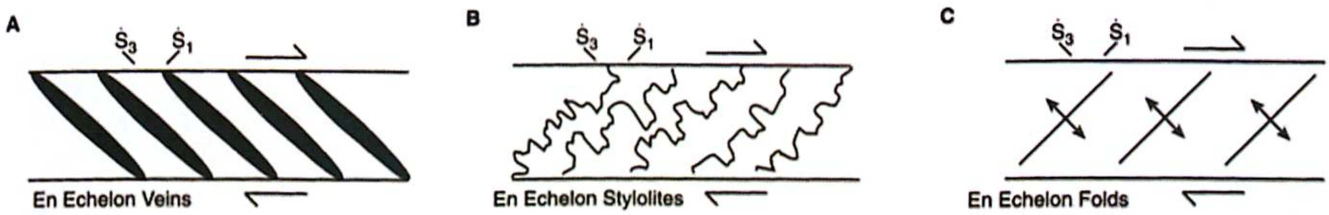


Strike-Slip Duplexes

(A) Extensional duplexes can form at releasing bends. (B) Compressional duplexes can form at restraining bends. Figures from Davis & Reynolds, 1996.

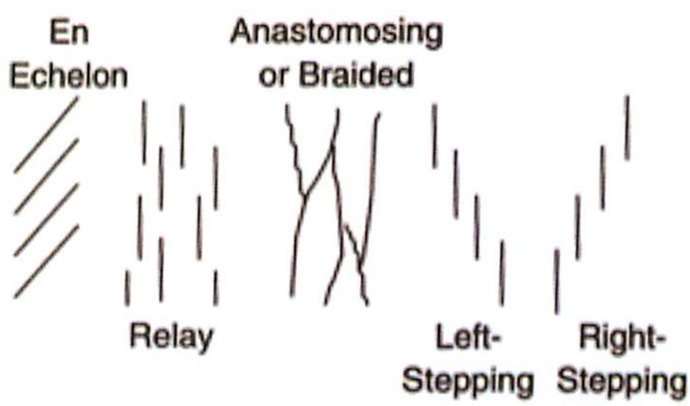
Slip Indicators in Strike-Slip Systems

In strike-slip systems, the maximum (S_1) and minimum compressional stresses (S_3) are at an angle with respect to the sense of shear. This can lead to the formation of both large scale folds and faults, or small scale fractures or veins, which are indicative to the sense of motion. Figures from Davis & Reynolds, 1996.



Even more Geometric Arrangements of Strike-Slip Faults

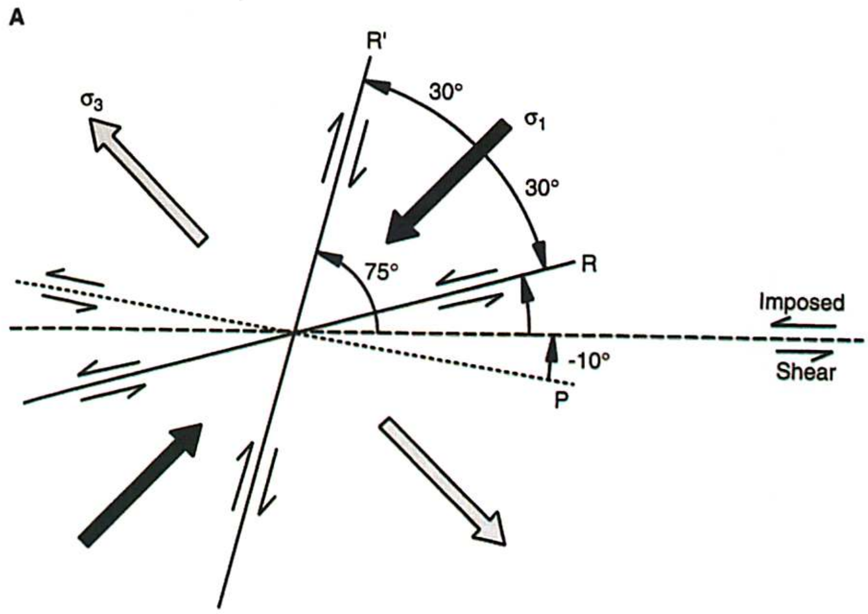
Figures from Davis & Reynolds, 1996.

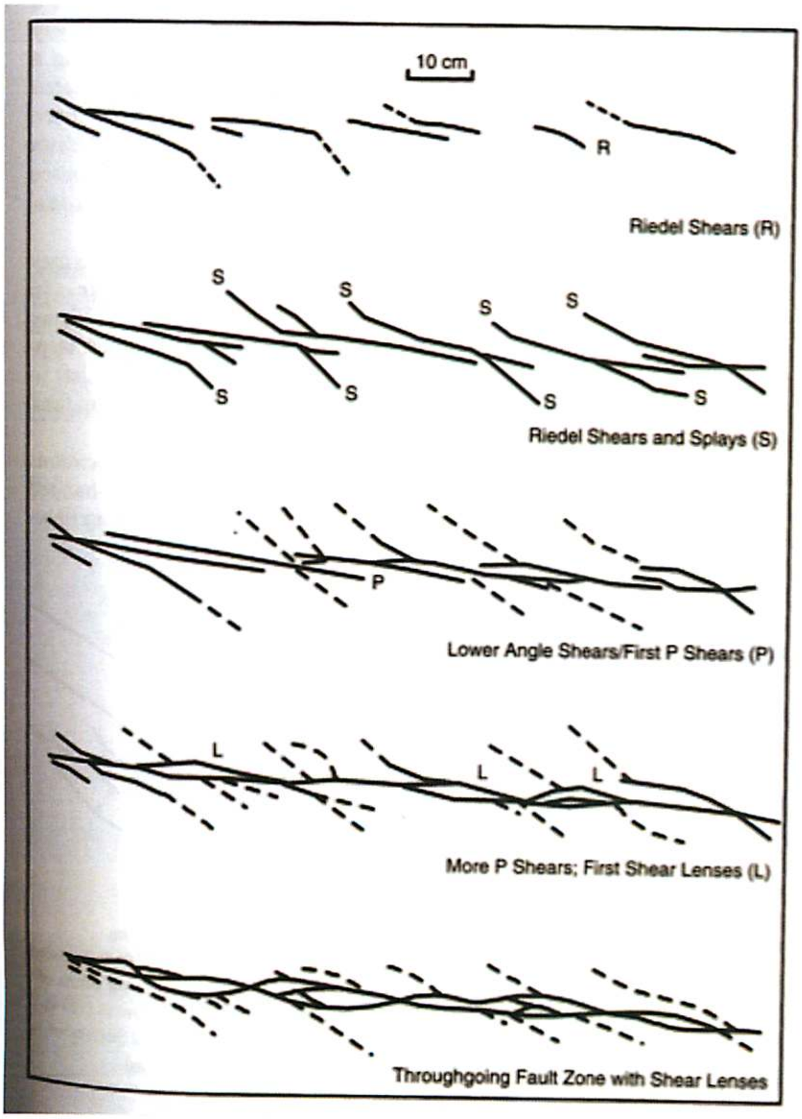


Structural Geology: Strike-Slip or Transform Faults

Riedel Shears

When under compression, rocks tend to form fail with faults forming 30° from the primary compressional stress. In a strike-slip fault, the primary compressional stress (σ_1) is 45° away from the plane of strike-slip shearing. The combination of these two facts results in fractures at interesting angles with respect to the motion of shear. These are called Riedel shears. The figure below shows a left-handed strike-slip zone. Figures from Davis & Reynolds, 1996.



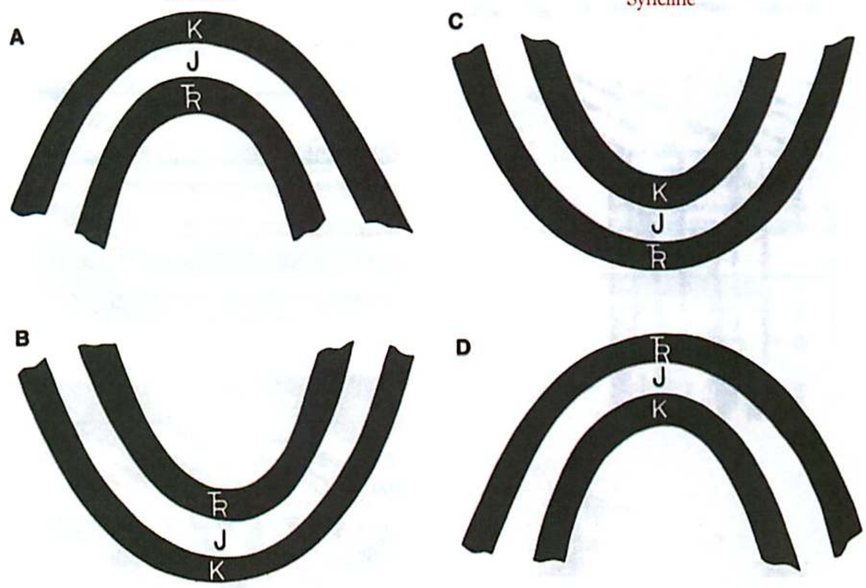


The figure at left illustrate the formation sequence of Riedel shears and other splays and shears in a right-handed strike-slip zone. Figures from Davis & Reynolds, 1996.

Structural Geology: Folds

Anticlines & Antiforms, and Synclines & Synforms

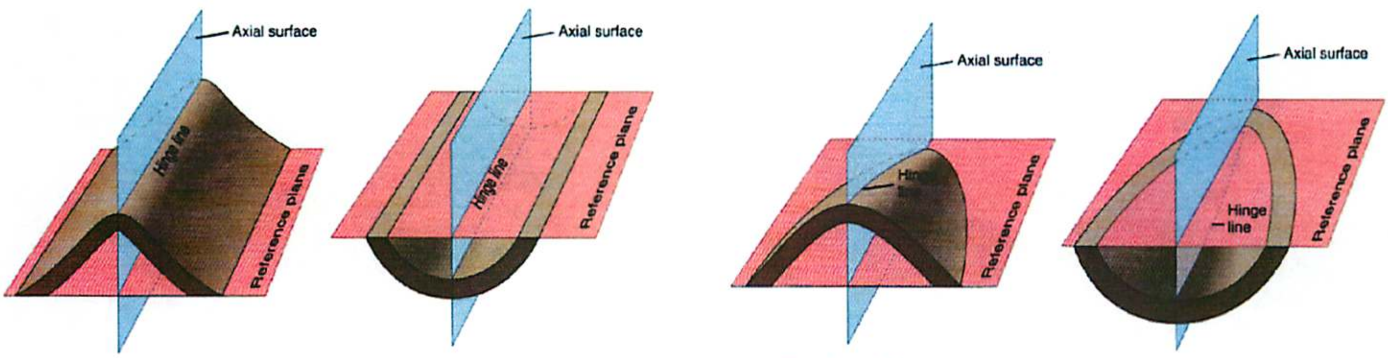
Antiforms are concave-down folds, while Synforms are concave-up folds. Anticlines are antiforms were we know that the younger strata lie on top of older strata. Similarly, Synclines are antiforms where younger strata lie on top of older strata. Figures from Davis & Reynolds, 1996.



Anticline | Syncline | Antiform | Synform

Plunging Folds

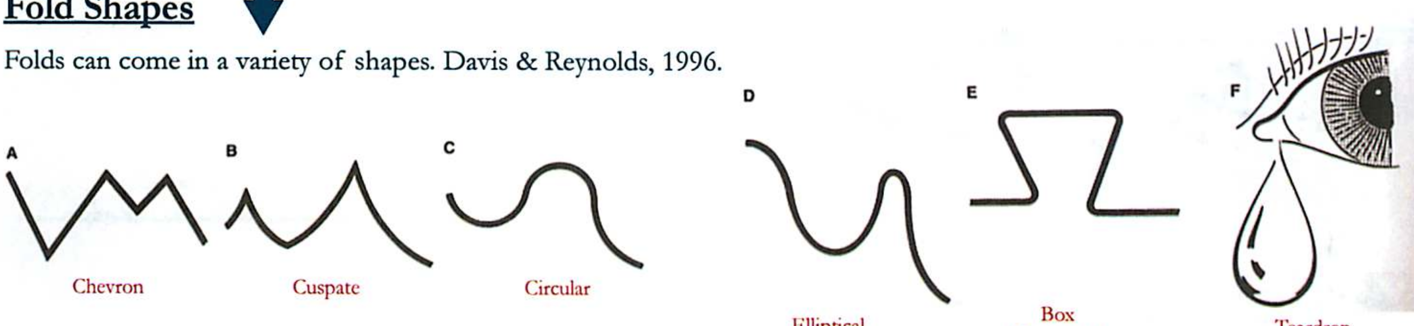
Folds (defined by hinge lines and axial surfaces) are not necessarily perpendicular to the Earth's surface. They can be dipping into or out of the surface. This can create interesting patterns of exposed surface rock, or even topography. Figures from Jones, 2001.



Non-plunging antiform | Non-plunging synform | Plunging antiform | Plunging synform

Fold Shapes

Folds can come in a variety of shapes. Davis & Reynolds, 1996.

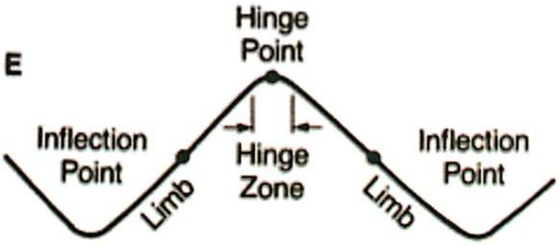


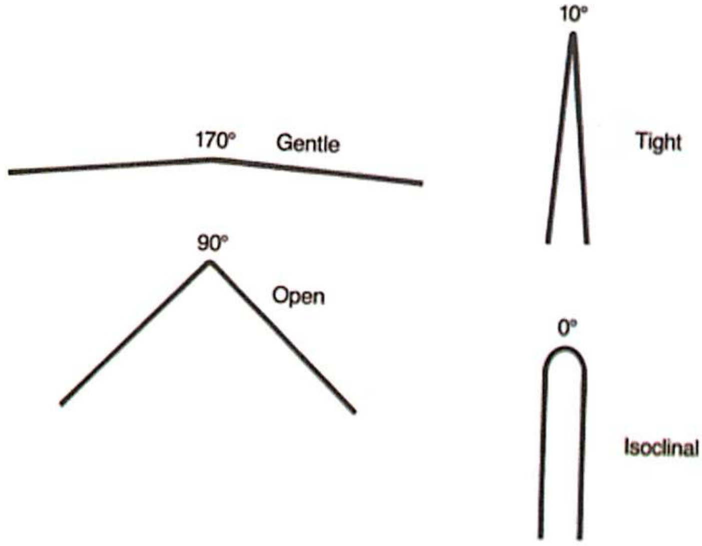
Chevron | Cuspate | Circular | Elliptical | Box (Conjugate) | Teardrop

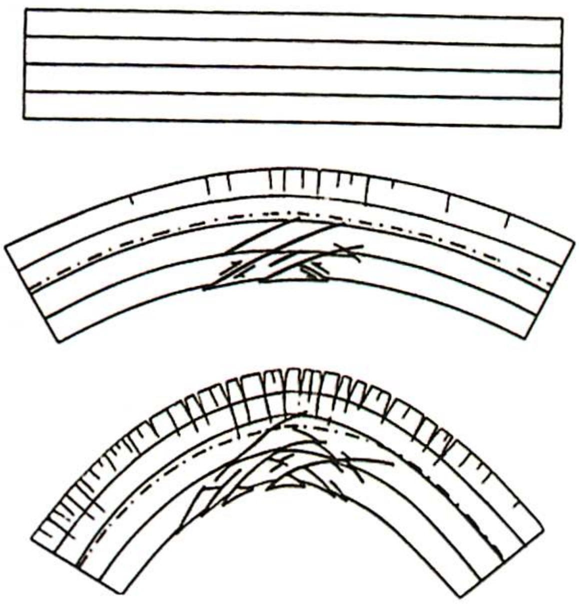
Structural Geology: Folds

Fold Tightness

Fold tightness is based upon the size of the inter-limb angle. Figures from Davis & Reynolds, 1996.





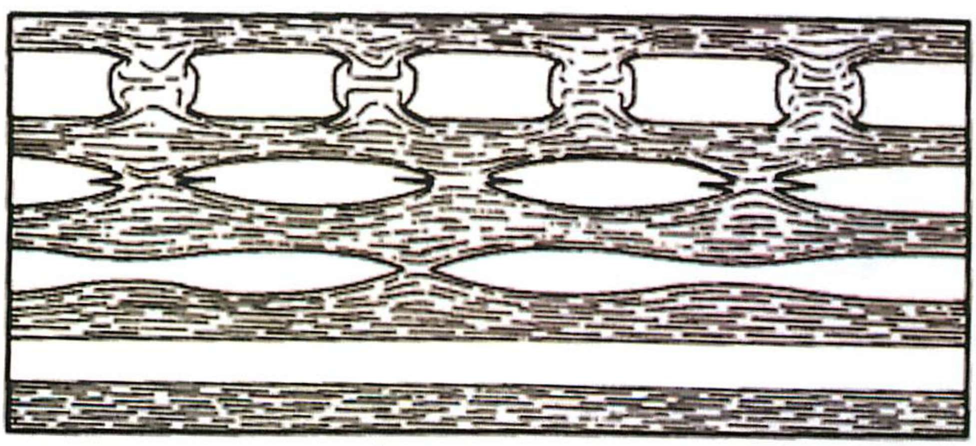


Minor Structures in Folds

When folding layers of strata, layer-parallel stretching occurs in the outer arc of a folded layer, while layer-parallel shortening occurs in the inner arc. Figures from Davis & Reynolds, 1996.

Boudins

Layer-parallel stretching can pinch off layers of strata, depending on the ductility contrast between layers. This can result in pinch-and-swell structures or boudins (where the pinching completely pinches off portions of a given strata). Figures from Davis & Reynolds, 1996.



Geologic Map Symbols

1 Contact, showing dip where trace is horizontal, and strike and dip where trace is inclined
2 Contact, located approximately (give limits)
3 Contact, located very approximately, or conjectural
4 Contact, concealed beneath mapped units
5 Contact, gradational (optional symbols)
6 Fault, nonspecific, well located (optional symbols)
7 Fault, nonspecific, located approximately
8 Fault, nonspecific, assumed (existence uncertain)
9 Fault, concealed beneath mapped units
10 Fault, high-angle, showing dip (left) and approximate dips
11 Fault, low-angle, showing approximate dip and strike and dip
12 Fault, high-angle normal (D or ball and bar on downthrown side)
13 Fault, reverse (R on upthrown side)
14 Fault, high-angle strike-slip (example is left lateral)
15 Fault, thrust (T on overthrust side)
16 Fault, low-angle normal or detachment (D on downthrown side)
17 Fault, low-angle strike-slip (example is right lateral)
18 Fault, low-angle, overturned (teeth in direction of dip)
19 Optional sets of symbols for different age-groups of faults
20 Fault zone or shear zone, width to scale (dip and other accessory symbols may be added)
21 Faults with arrows showing plunge of rolls, grooves or slickensides
22 Fault showing bearing and plunge of net slip
23. Point of inflection (bar) on a high-angle fault
24 Points of inflection on a strike-slip fault passing into a thrust
25 Fault intruded by a dike
26 Faults associated with veins
27 Anticline, showing trace and plunge of hinge or crest line (specify)
28 Syncline (as above), showing dip of axial surface or trough surface
29 Folds (as above), located approximately
30 Folds, conjectural
31 Folds beneath mapped units
32 Asymmetric folds with steeper limbs dipping north (optional symbols)
33 Anticline (top) and syncline, overturned
34 Antiformal (inverted) syncline
35 Synformal (inverted) anticline
36 Antiform (top) and synform (stratigraphic sequence unknown)
37 Separate dome (left) and basin
38 Culmination (left) and depression
40 Vertically plunging anticline and syncline
41 Monocline, south-facing, showing traces of axial surfaces
42 Steeply plunging monocline or flexure, showing trace in horizontal section and plunge of hinges
43 Plunge of hinge lines of small folds, showing shapes in horizontal section
44 Strike and dip of beds or bedding
45 Strike and dip of overturned beds
46 Strike and dip of beds where stratigraphic tops are known from primary features
47 Strike and dip of vertical beds or bedding (dot is on side known to be stratigraphically the top)
48 Horizontal beds or bedding (as above)
49 Approximate (typically estimated) strike and dip of beds
50 Strike of beds exact but dip approximate
51 Trace of single bed, showing dip where trace is horizontal and where it is inclined
52 Strike and dip of foliation (optional symbols)
53 Strike of vertical foliation
54 Horizontal foliation
55 Strike and dip of bedding and parallel foliation
56 Strike and dip of joints (left) and dikes (optional symbols)
57 Vertical joints (left) and dikes
58 Horizontal *joints (left) and dikes*
59 Strike and dip of veins (optional symbols)
60 Vertical veins
61 Horizontal veins
62 Bearing (trend) and plunge of lineation
63 Vertical and horizontal lineations
64 Bearing and plunge of cleavage-bedding intersection
65 Bearing and plunge of cleavage-cleavage intersections
66 Bearings of pebble, mineral, etc. lineations
67 Bearing of lineations in plane of foliation
68 Horizontal lineation in plane of foliation
69 Vertical lineation in plane of vertical foliation
70 Bearing of current from primary features; from upper left: general; from cross-bedding; from flute casts; from imbrication
71 Bearing of wind direction from dune forms (left) and cross-bedding
72 Bearing of ice flow from striations (left) and orientation of striations
73 Bearing of ice flow from drumlins
74 Bearing of ice flow from crag and tail forms
75 Spring
76 Thermal spring
77 Mineral spring
78 Asphaltic deposit
79 Bituminous deposit
80 Sand, gravel, clay, or placer pit

From Compton, 1985

Geologic Map Symbols

81	Mine, quarry, or open pit
82	Shafts: vertical, inclined, and abandoned
83	Adit, open (left) and inaccessible
84	Trench (left) and prospect
85	Water wells: flowing, nonflowing, and dry
86	Oil well (left) and gas well
87	Well drilled for oil or gas, dry
88	Wells with shows of oil (left) and gas
89	Oil or gas well, abandoned (left) and shut in
90	Drilling well or well location
91	Glory hole, open pit, or quarry, to scale
92	Dump or fill, to scale

Fossil and Structural Symbols for Stratigraphic Columns

- Algae
- Algal mats
- Ammonites
- Belemnites
- Brachiopods
- Bryozoans
- Corals, solitary
- Corals, colonial
- Crinoids
- Echinoderms
- Echinoids
- Fish bones
- Fish scales

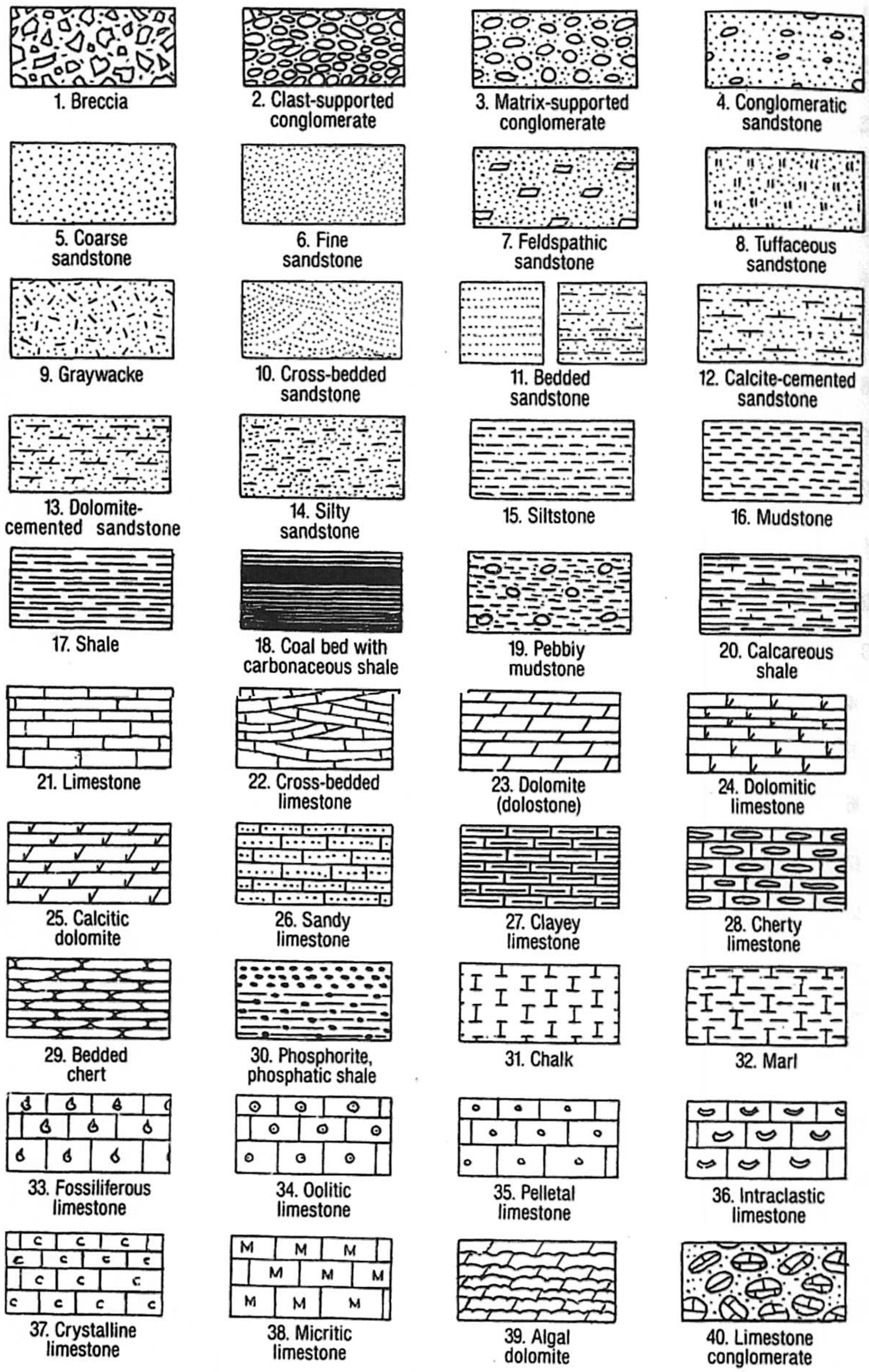
- Tree trunk fallen
- Trilobites
- Vertebrates
- Wood
- Beds distinct
- Beds obscure
- Unbedded
- Graded beds
- Planar cross-bedding
- Trough cross-bedding
- Ripple structures
- Cut and fill
- Load casts

- Foraminifers, general
- Foraminifers, large
- Fossils
- Fossils abundant
- Fossils sparse
- Gastropods
- Graptolites
- Leaves
- Ostracodes
- Pelecypods
- Root molds
- Spicules
- Stromatolites
- Tree trunk in place

- Scour casts
- Convolution
- Slumped beds
- Paleosol
- Mud cracks
- Salt molds
- Burrows
- Pellets
- Oolites
- Pisolites
- Intraclasts
- Stylolite
- Concretion
- Calcitic concretion

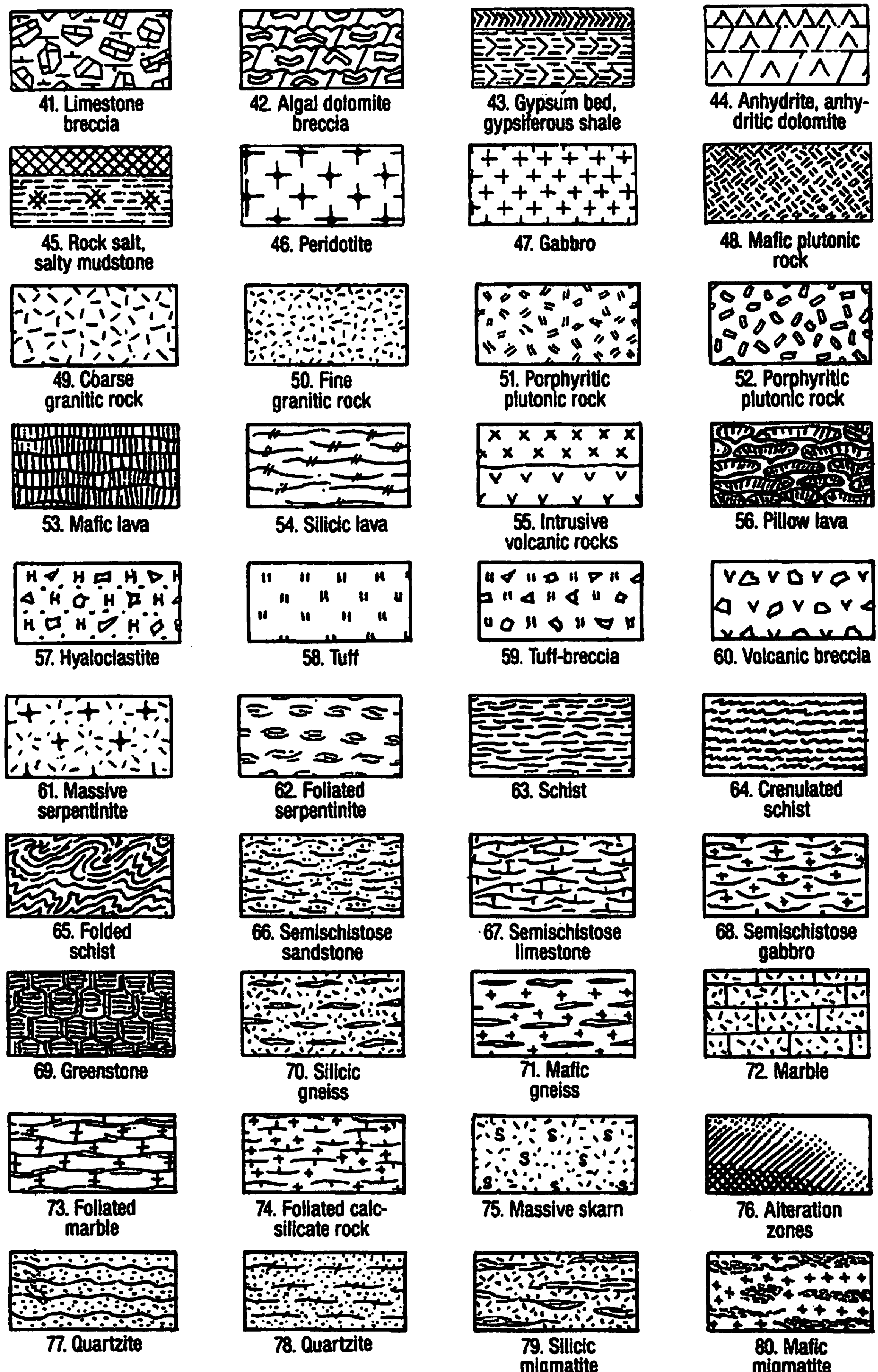
From Compton, 1985

Lithologic Patterns for Stratigraphic Columns & Cross Sections



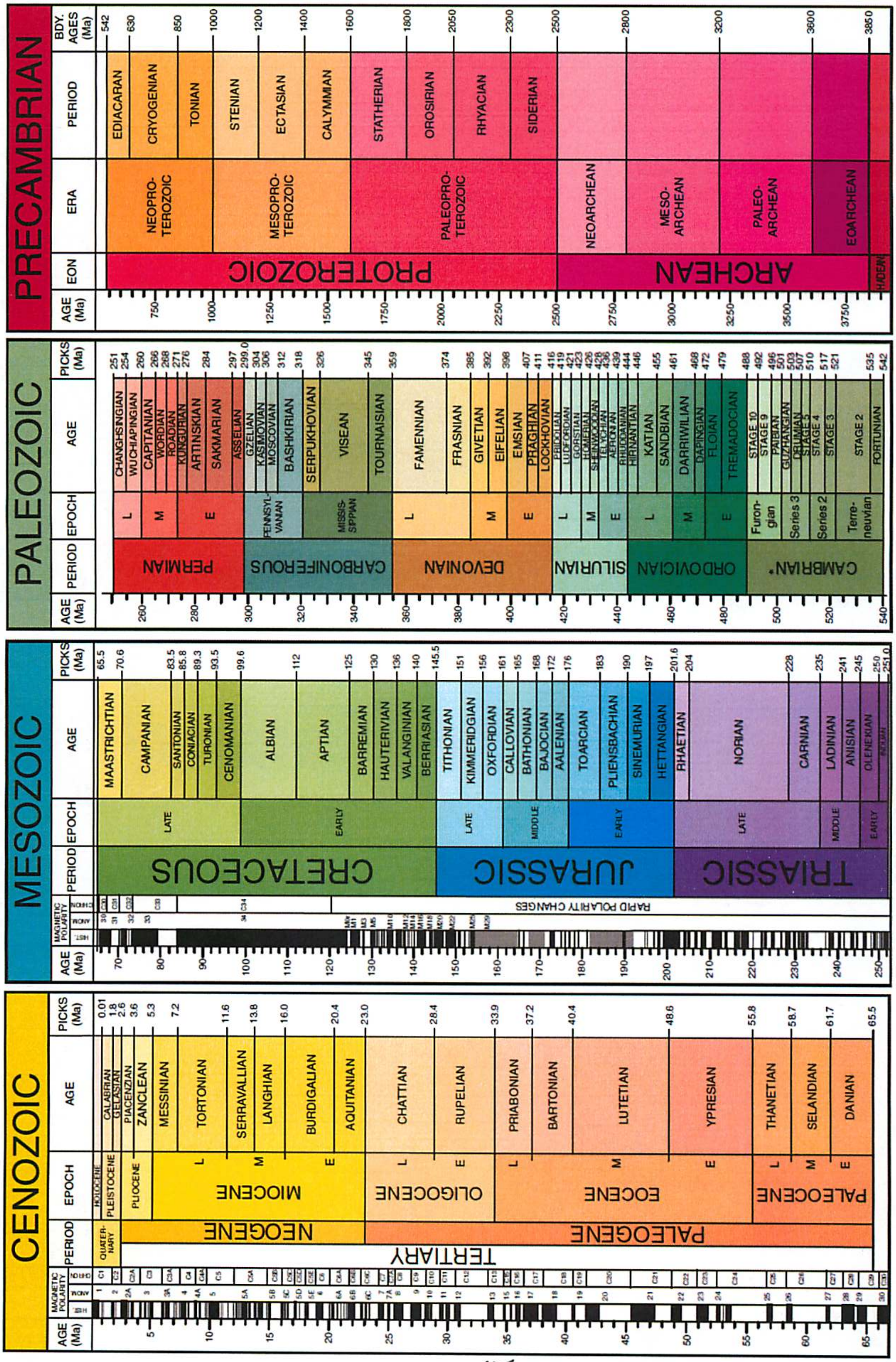
From Compton, 1985

Lithologic Patterns for Stratigraphic Columns & Cross Sections



From Compton, 1985

Geologic Timescale



2009 version, from the Geologic Society of A

Farallon plate activity in the Cretaceous and Tertiary

Youngmin JeongAhn

The **Farallon plate** is an ancient oceanic plate which has been **subducted below the North American plate**. The name was given after the Farallon islands located off the coast of San Francisco. The northern and southern remnants of the Farallon plate are called the **Juan de Fuca** and **Cocos plate**, respectively.

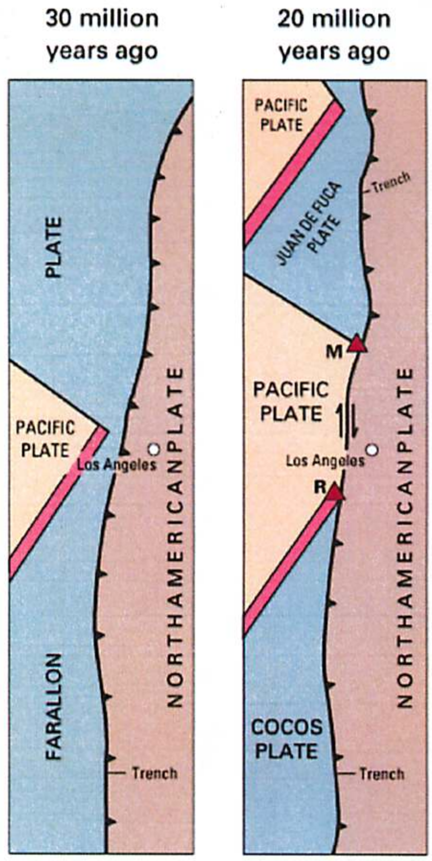
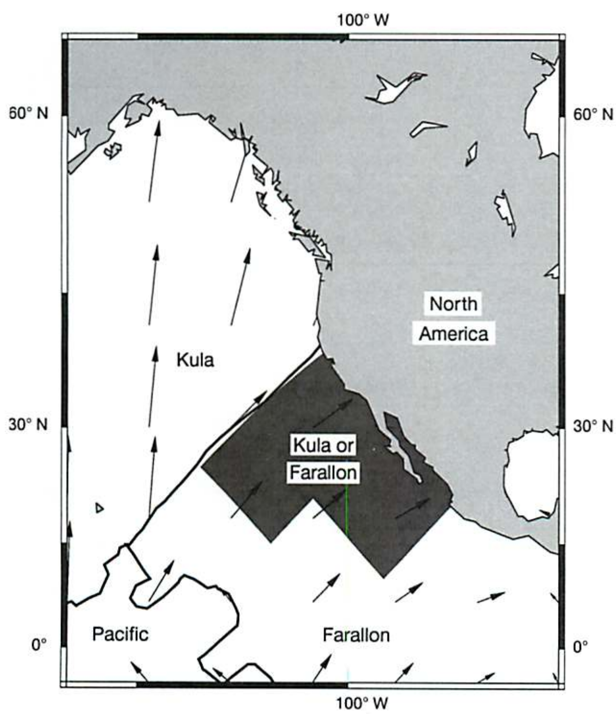


Image from USGS

During the Mesozoic Era

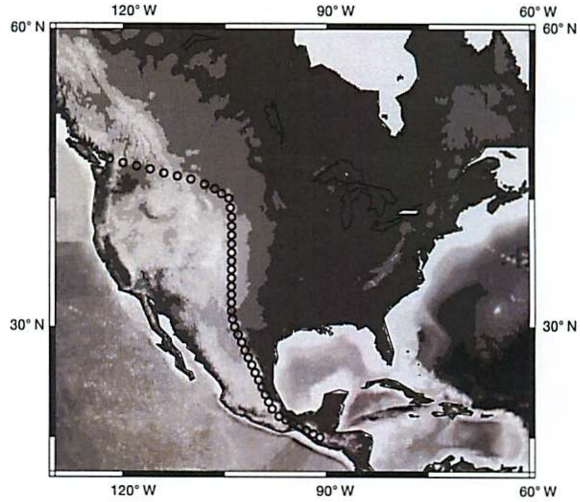
As the Farallon plate was subducting beneath the North American plate, the western North America plate received **compressional force** and profound mountain system was developed due to shortening. Frictional heat during subduction generated magma, which developed **volcanic arcs** in Sierra Nevada. **Thrust faults** and **crustal uplift** formed Sevier orogeny.



Between 65Myr and 74Myr ago (Bunge & Grand, 2000)

The **Kula plate** is another oceanic plate lost by subduction with the Farallon plate. The exact boundary between the Kula and Farallon plate is uncertain because they are now located in the lower mantle and only a high-resolution tomographic study can barely reveals their structure.

The angle of subduction in this early stage was steep and it became shallower in the later stage. The boundary of area affected by low dipping angle extends from Alaska to the southern Gulf of Mexico.



Boundary of the shallow subduction of the Farallon plate (Bunge & Grand, 2000)

During the Tertiary

The shallow angle of subduction heated up the overlying thick crust and suddenly moved active volcanic regions from Sierra Nevada to Colorado around 70 Myr ago. Volcanic activity gradually migrated westward and crust in northern Colorado, Wyoming and Montana uplifted. This mountain-creating period is called **Laramide orogeny**.

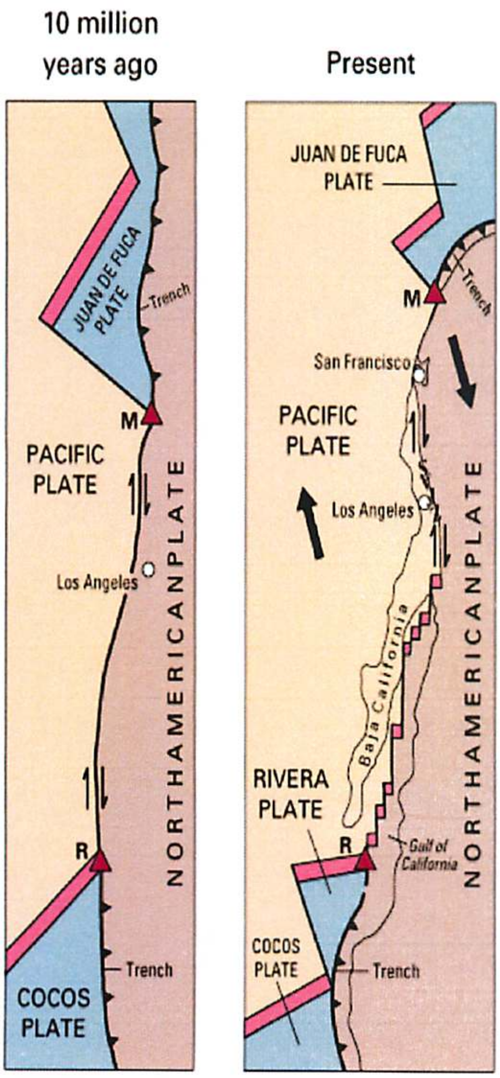
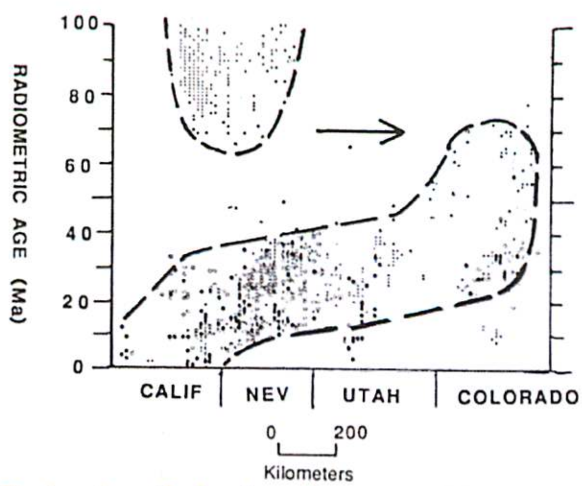


Image from USGS

The spreading center of the Farallon plate met the North American plate and the plate was broken apart into smaller parts around 30 Myr ago. Laramide orogeny ended at this time and Sevier-Mogollon range begins to collapse.

Basin and Range Province was developed by lithospheric extension from 17 Myr ago. Crustal extension develops normal faults, horsts, and grabens. Our town, Tucson is located on the basin formed by this extensional force. (Ask Kat for the detail!).



The location of volcanic and igneous activity (Atwater 1989)

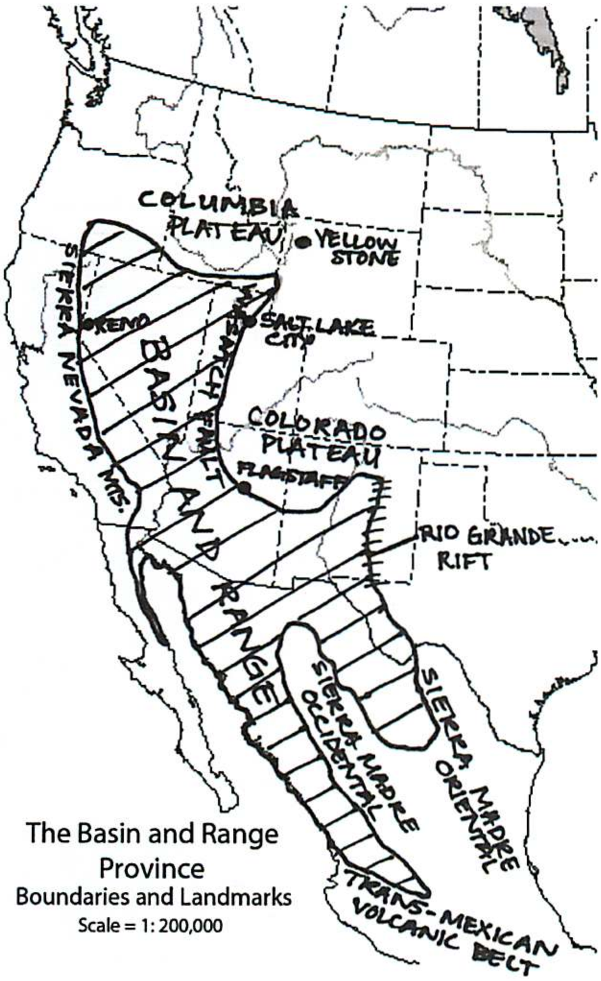
Basin and Range Geology

Kat Volk

The **basin and range province** is a result of extensional tectonic activity in the southwest.

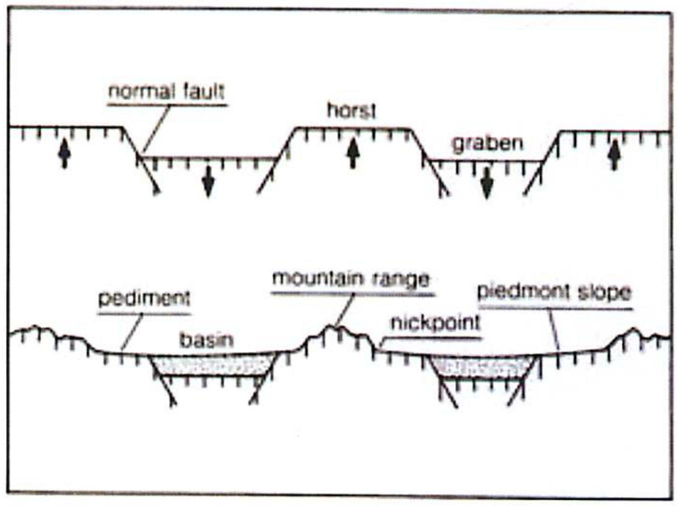
It is characterized by numerous mountain ranges rising out of plain-like basins. The mountain ranges are typically a few to a few tens of km apart.

The idealized way they form is via normal faulting. Extension creates movement along normal faults generating a horst and graben terrain, which then evolves to form basin and range terrain.

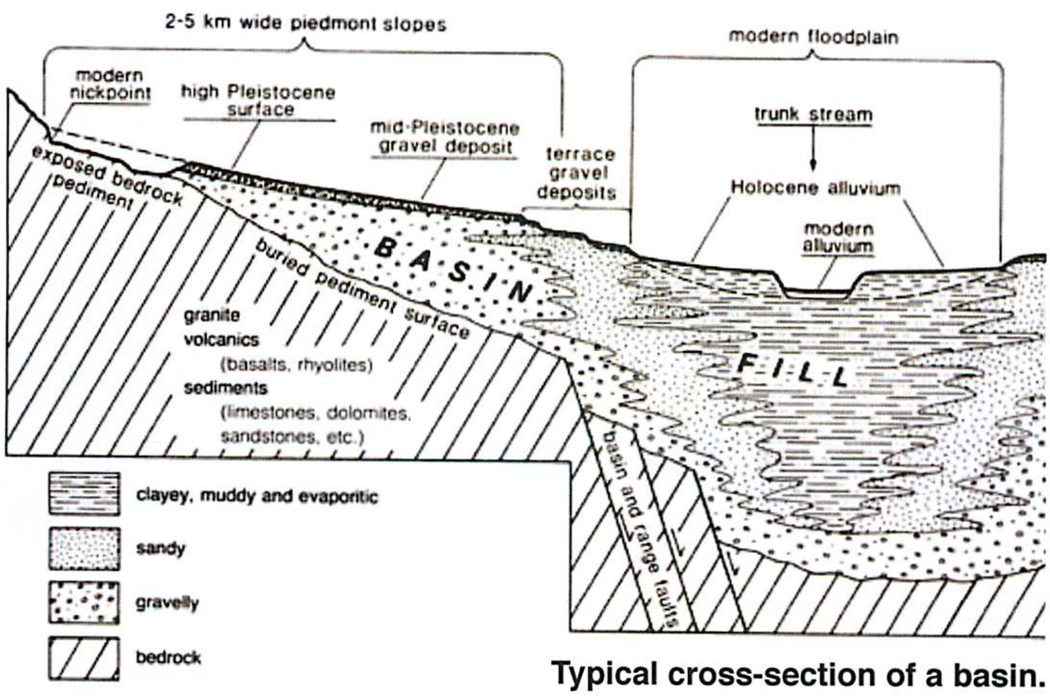


The Basin and Range Province
Boundaries and Landmarks
Scale = 1: 200,000

Image credit: Kathleen Smith compiled from Dickinson 2002



Hendricks 1985



Typical cross-section of a basin.

Basin and range terrain can also form from half-graben (tilted blocks).

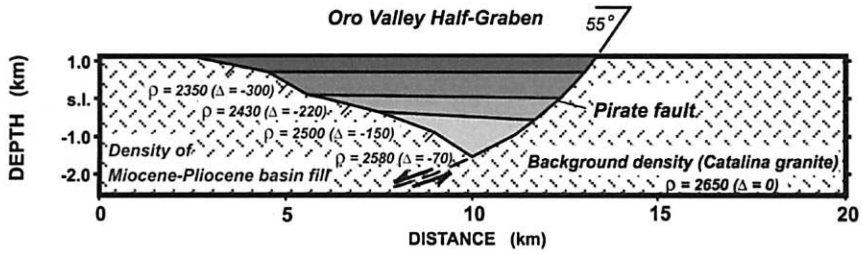
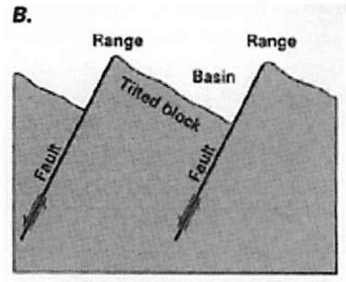


Figure 5. Interpretation of Pirate fault geometry and displacement based on gravity modeling of Oro Valley basin fill. Shadings in Oro Valley basin fill denote different model densities ρ; δ values are density contrasts between basin fill and bedrock basement.

Davis et al. 2004



USGS

Evolution of Basin and Range Landscape

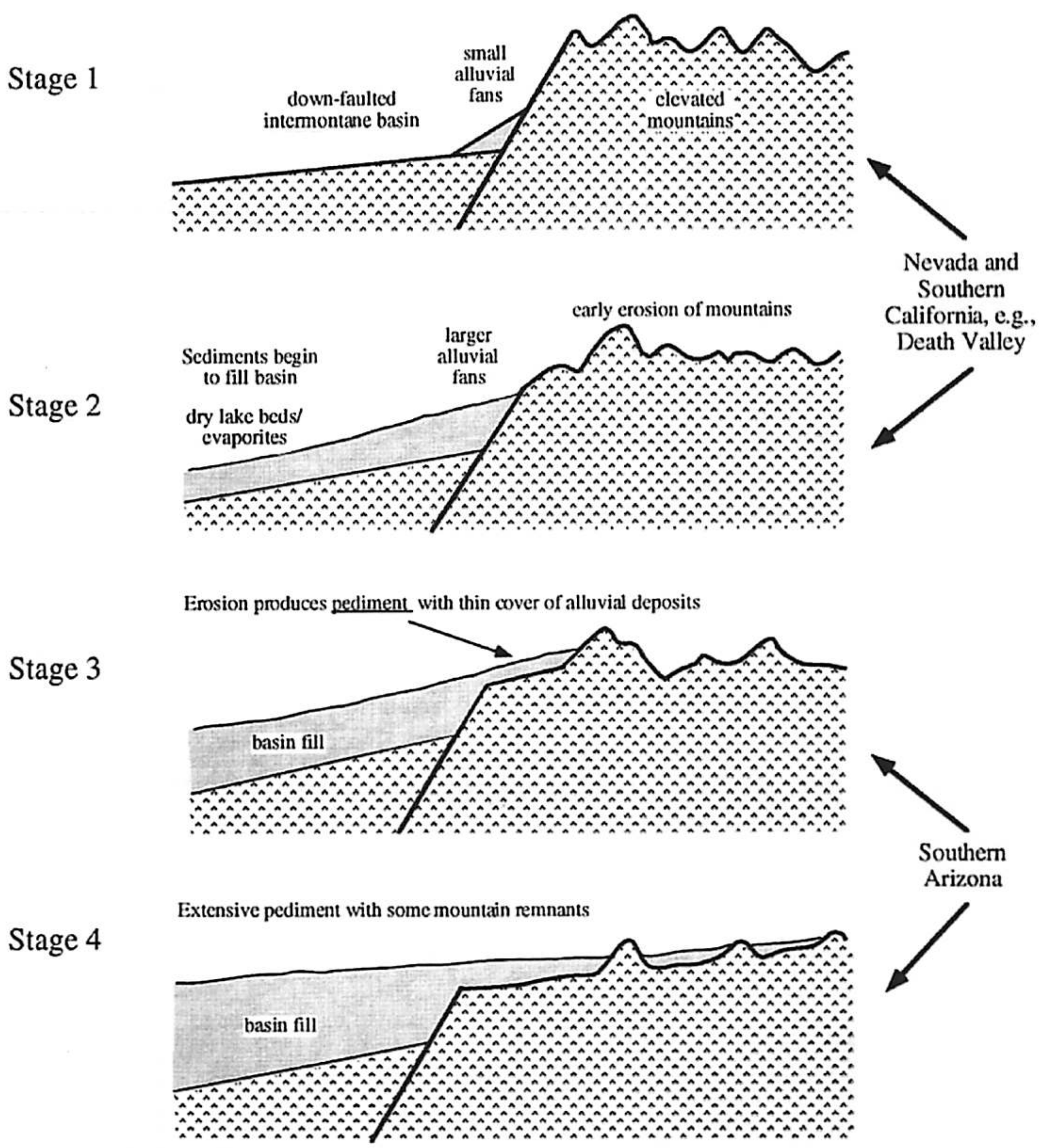


image source: http://www.saguaro-juniper.com/i_and_i/geology/geology_walk/3_basinrange.html

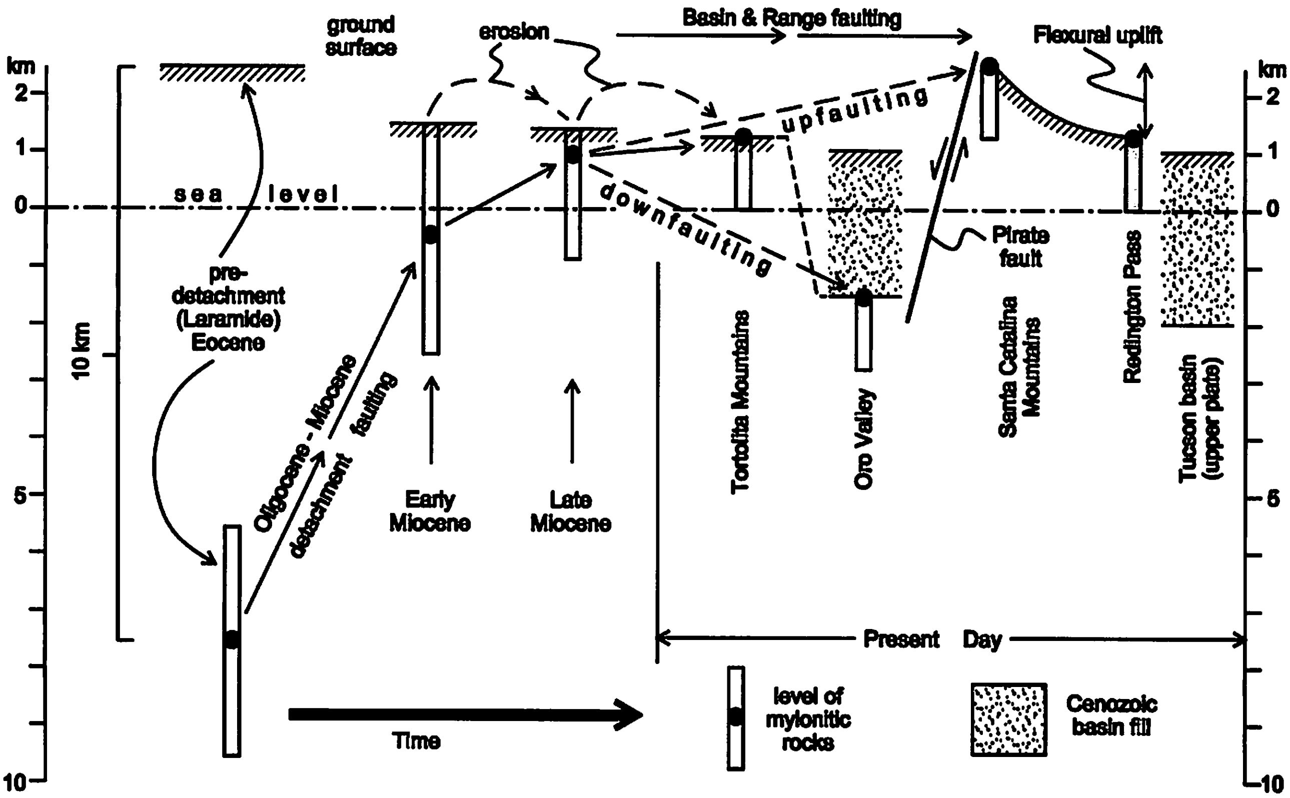


Figure 11. Summary diagram of incremental (left to right) exhumation and uplift of mylonitic rocks in Catalina-Rincon metamorphic core complex (see text discussions for controls on changing elevations of ground surface and burial depths of mylonitic rocks); sediment thickness in Tucson basin after Eberly and Stanley (1978) and Houser and Gettings (2000).

Figure and timeline from Davis et al. 2004:

Extension in the southwest started ~30 Myr ago in the late Oligocene/early Miocene:
- accommodated in shear zones which generated metamorphic core complexes associated with detachment faults (which James and Donna cover)

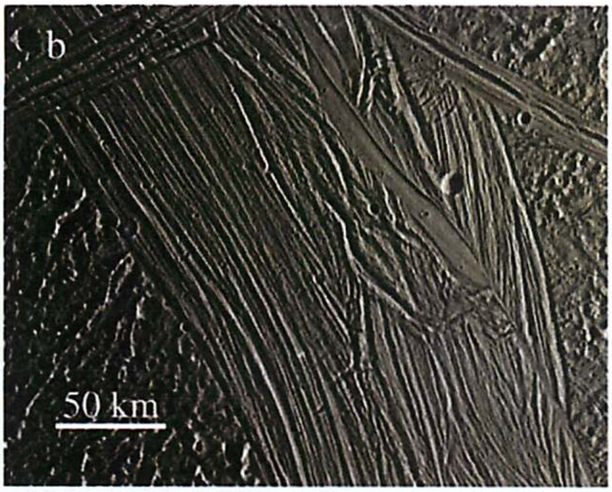
Early Miocene (**~20-25 Myr ago**):
- faulting tended to start at high dip angles but rotate to lower dips as the blocks tilted

Post-middle Miocene (**~17 Myr ago**)
- extension is accommodated by high angle normal faults
- most rapid basin and range extension happens right before the onset of seafloor spreading in the golf of California

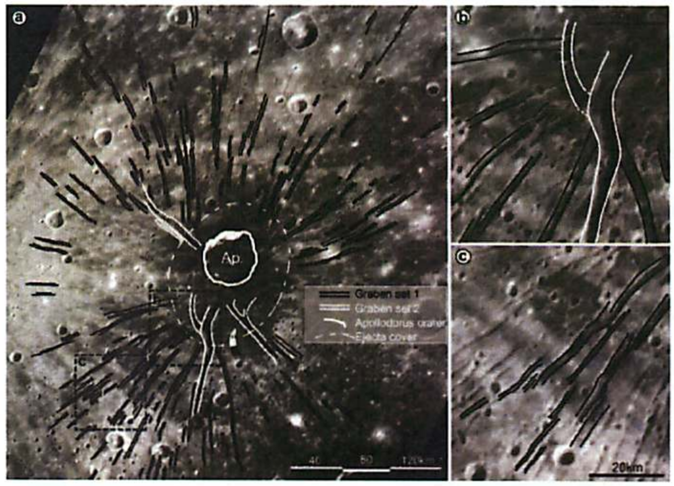
Present:
- extension continues, but at a lower rate

Planetary Connections:

We see plenty of extensional features on other bodies:



extensional features on Europa (Nimmo 2004)



Graben on Mercury (Klimczack et al. 2010)

But there are no other examples of basin and range terrain.

References

Dickinson, William R. "The Basin and Range Province as a Composite Extensional Domain". International Geology Review, Vol. 22, 2002

Hendricks, David M. Arizona Soils. 1985 (http://southwest.library.arizona.edu/azso/index.html)

Davis et al. “Fault and fault-rock characteristics associated with Cenozoic extension and core-complex evolution in the Catalina-Rincon region, southeastern Arizona.” GSA Bulletin, January/February, v. 116, no. 1/2, p. 128–141, 2004.

Debris flows are a common feature of southern Arizona, particularly in the Santa Catalina Mountains. Locally, recently, they are most connected with water. However, throughout the solar system, similar features can have other causes.

During a debris flow, solid, rocky material acts like a liquid through a process called granular convection. In granular convection, the different particles vibrate, contributing to the liquid-like behavior. Granular convection is sometimes called the Brazil nut effect or the muesli effect.

In southern Arizona, debris flows are common after heavy rains and flooding. In 2006, heavy, record-setting rains triggered numerous debris flows in the Santa Catalina Mountains The majority of the debris flows in the area happened in river-carved channels, such as Sabino Canyon and Rattlesnake Canyon (see figure 1). In southern Arizona, these events are strongly associated with water action (Webb et al 2008).

This process has happened in the Tucson area since prehistoric times; the 2006 events were simply particularly well-documented. The same trigger, heavy precipitation is largely cited as the cause. Studying the rocks from previous debris flows shows evidence of granular convection with the characteristic lack of sorting due to granular convection. They can be dated by their level of weathering, carbonate coatings, and level of vegetation (Youberg et al 2008).

Debris flows do happen on other planets. For examples, debris flows have been observed on Venus, Mars, and Saturn's moon Titan. However, the exact mechanisms vary considerably from those in the Tucson area. These mechanisms can involve everything from volcanic activity to liquid hydrocarbons en lieu of heavy rains.

The planet Venus has detectable debris flows. For example, the Baltis Vallis channel contains many features associated with terrestrial rivers, including debris flows. However, despite debate on the erosional/constructional nature of the channel, it is clearly volcanic in origin (see figure 2). Even though the channel had nothing to do with water, it still displays debris flows (Oshigami and Namiki 2007).

On Mars, debris flows are interpreted as evidence for surface water. According to Costard et al, various debris flows observed in the MOC images closely resemble periglacial debris flows observed on Earth, such as those in Greenland (see figures 3,4). Based on these observations, the researchers reached the conclusion that the debris flows could be caused by water ice and possibly even liquid water within the first few meters of the surface of Mars. However, they also stated that thes liquid flows are probably transient, and could represent the extremes of Martian conditions (Costard et al 2001).

As a fun side note, a debris flow on Mars was featured in

Kim Stanley Robison's award-winning Mars trilogy.

Saturn's moon Titan may also have fluid-related debris flows. The moon, also called Saturn VI, is a rarity in the Sol system, a moon that has an atmosphere. However, conditions are radically different on Titan from those on Earth. Liquid hydrocarbons may mimic the hydrological cycle on Earth. Debris flows have been observed by the Cassini probe. Like the flows on Earth, the debris flows on Titan are associated with rivers. However, the rivers of Titan are composed of liquid methane rather than water. Additionally, cryovolcanism might also contribute to debris flows (Stofan et al 2009).

Debris flows like the ones in Tucson can be observed on several other planets. However, while the ones in Tucson are associated with heavy rains, a variety of other mechanisms are observed throughout the solar system. Cryovolcanism, volcanic activity, and even non-water liquids can produce very similar results.

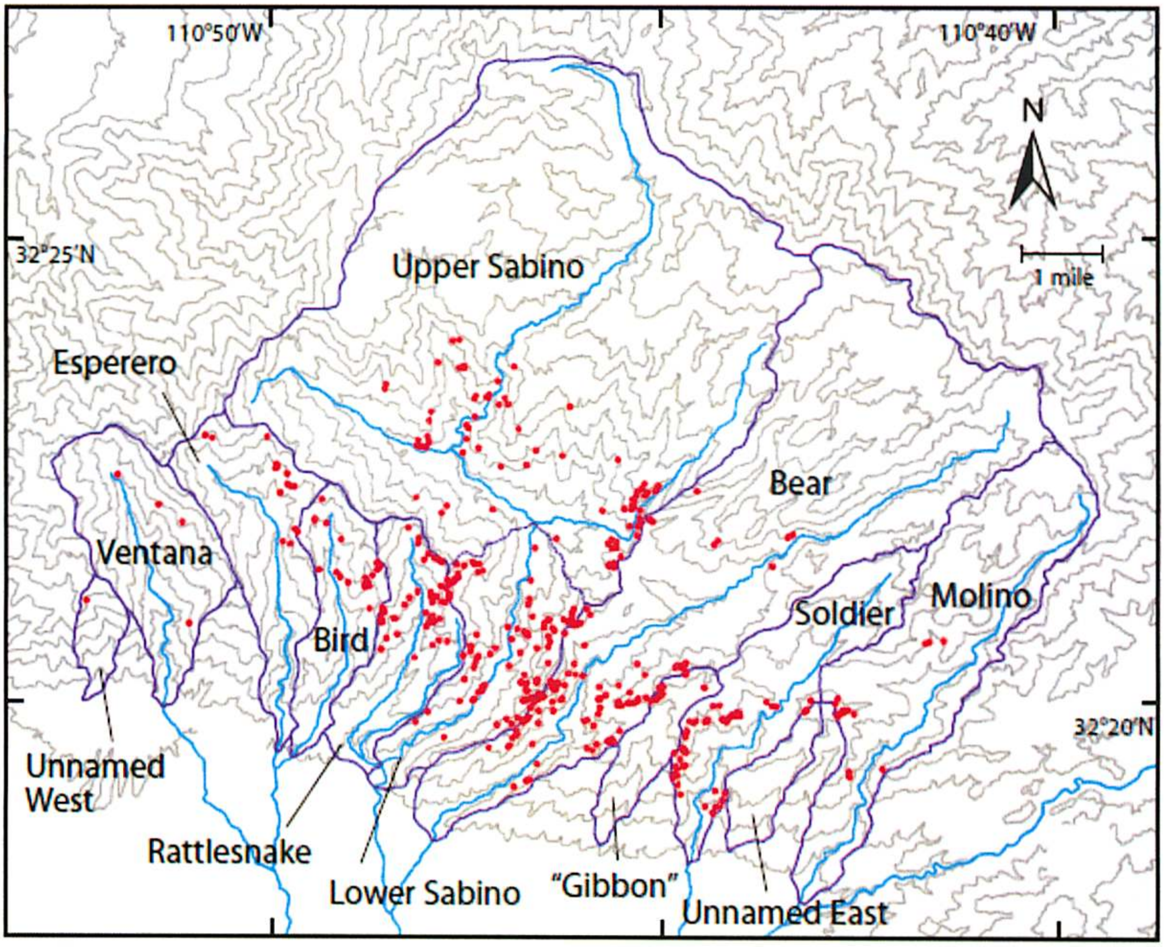


Figure 1: July 2006 debris flows, photo by USGS.

Figure 2: The Baltis Vallis, ~49.6 N, 166.4 E, from Oshigami and Namiki 2007.

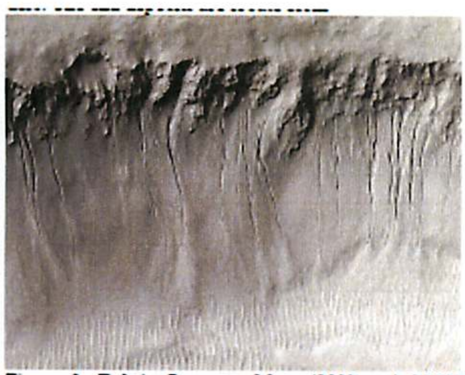


Figure 3: Debris flows on Mars, (29S and 39W), MOC image MSS

Figure 4: Debris flows in East Greenland by Costard and Peulvast 1987.

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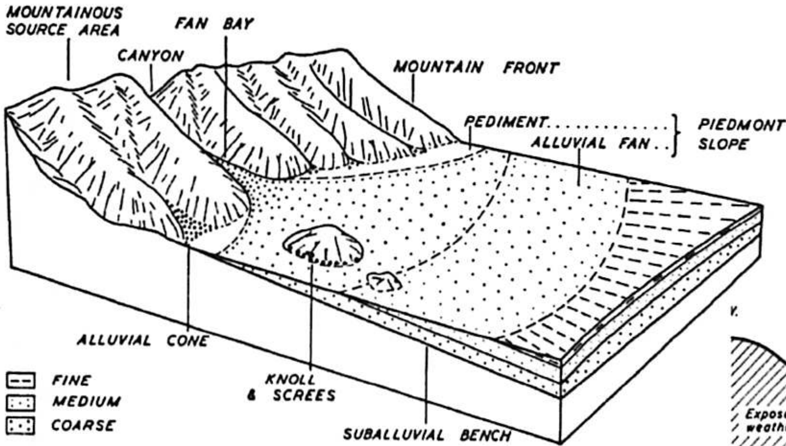
Pediments

Sarah Morrison

Definition: smooth, mostly unincised, low slope (0-10°) bedrock surfaces that are dynamic, erosional landforms at the foot of mountain ranges



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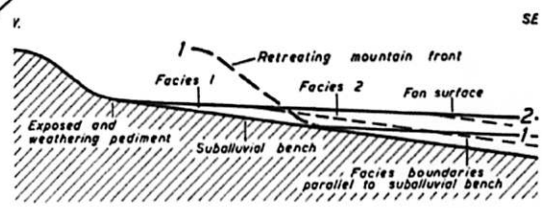
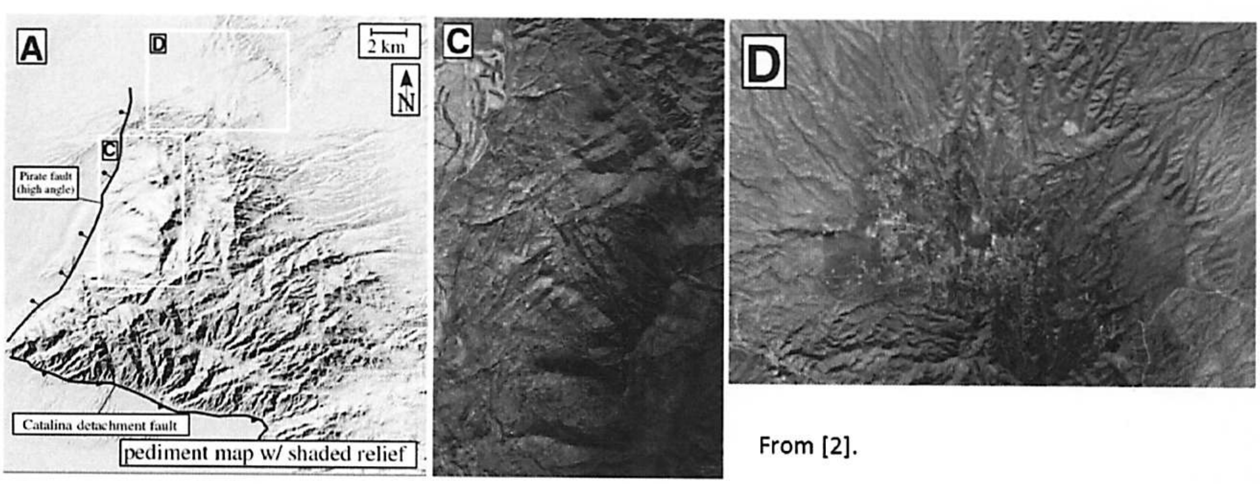


Retreating of the mountain front can lengthen pediments, but recent modeling suggests tectonic tilting due to isostatic rebound relative to the rest of the basin and range also facilitates the formation of pediments and produces no correlation between slope and length of the pediment [2]. For pediments to form, the rate of erosion must equal or exceed the rate of soil production on the piedmont [2,3]. Since fluvial incision and deep bedrock weathering must also be suppressed, pediments tend to form in arid environments [2,3].

Pediments in the Santa Catalina mountains are best developed on the north (Oracle pediment, D) and west side (Catalina Pediment, C) of the range and are largely composed of granite and mylonitic gneiss (same make-up as the mountains themselves) [2].



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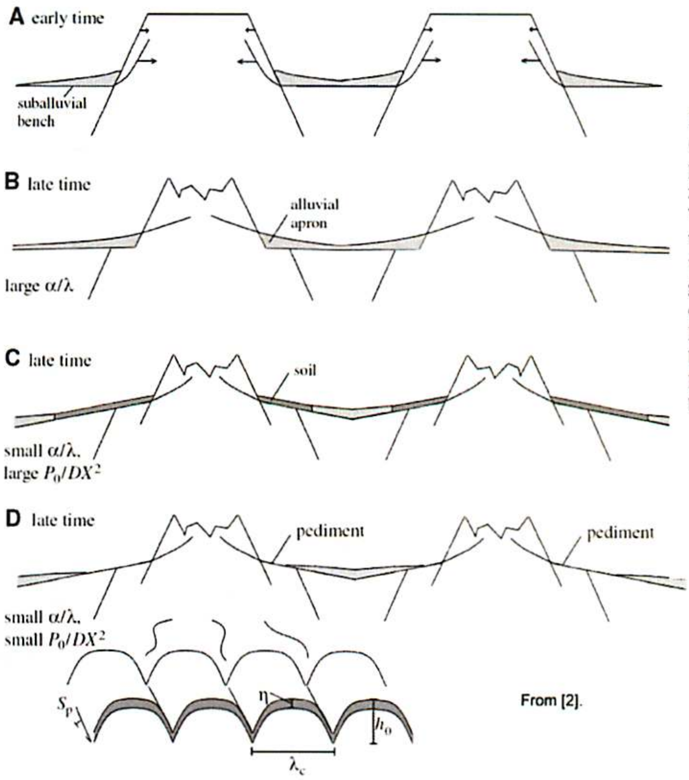


From [2].

Figure 2. Schematic diagram of the conceptual model. Early in the model, Basin and Range extension creates a semi-periodic series of basins and ranges. Range-bounding hillslopes and channels respond by backwearing and downwearing. The erosional response to uplift is accompanied by a flexural-isostatic rebound. If the value of α/λ is relatively large, isostatic rebound will be distributed across basins and range uniformly, resulting in little or no piedmont tilting (B). As a result, the piedmont will remain covered in alluvium. If, however, the value of α/λ is relatively small, the piedmont will tilt. Pediments will form on the tilted piedmont if the value of P_0/DX^2 is relatively small. In that case (D), hillslope and channel erosion on the piedmont will keep pace with soil production, resulting in bare bedrock slopes despite the low relief (as in Fig. 1). If the value of P_0/DX^2 is relatively large, a soil will form on the tilted piedmont slope. Also shown in (D) are parameters of the hillslope model (i.e., S_p, η, λ_c, and h_0) used to determine the critical value of P_0/DX^2 required for bare slopes to form.

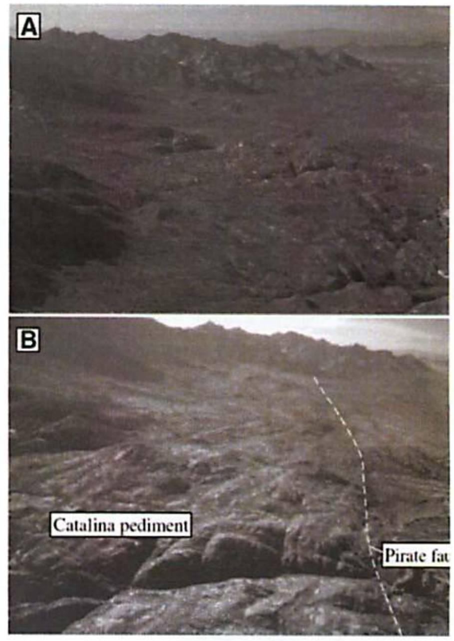
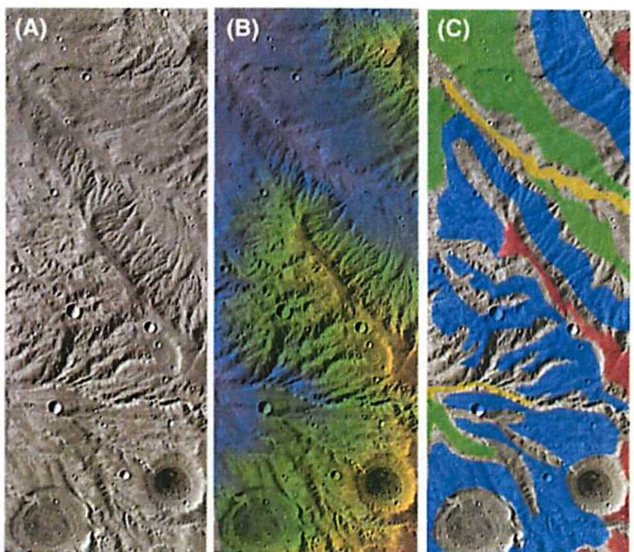


Figure 1. Aerial photographs (south looking) of the Catalina pediment near Catalina, Arizona (northwest of Tucson). The close-up view (B) illustrates that the pediment is dissected with bedrock channels that grade into the steeper bedrock channels of the Santa Catalina Mountains. The pediment is bounded on its west side by the Pirate Fault. Aerial Photography by Peter L. Kresan ©1990.

From [2].

Mars likely has pediments associated with fan deposits. As shown in the Margaritifer Sinus region of Mars, alternating episodes of erosion and incision led to the formation and subsequent fluvial incision of pediments and fans, which produces similar sets of pediments/fans to those found in the southwestern United States [4].



From [4].

Figure 16. Pediments and fans in Margaritifer Sinus region. (a) THEMIS daytime IR image I01686001. (b) Image with elevation cueing. (c) Interpretation based upon landforms northeast of the central ridge (red) and speculatively extended elsewhere. Age sequence from oldest to youngest is red-blue-green-yellow (final drainage level). Image located at 357.02°E, 25.86°S. Image width 31 km.

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Joint formation and control of Valley creation

Ning Ding

1.General Information

Joint: In geology the term joint refers to a fracture in rock where the displacement associated with the opening of the fracture is greater than the displacement due to lateral movement in the plane of the fracture (up, down or sideways) of one side relative to the other. Joints normally have a regular spacing related to either the mechanical properties of the individual rock or the thickness of the layer involved. Joints generally occur as sets, with each set consisting of joints sub-parallel to each other. [1]

Valley: In geology, a valley or dale is a depression with predominant extent in one direction. A very deep river valley may be called a canyon or gorge. The terms U-shaped and V-shaped are descriptive terms of geography to characterize the form of valleys. Most valleys belong to one of these two main types or a mixture of them, (at least) with respect of the cross section of the slopes or hillsides. A valley formed by flowing water, or river valley, is usually V-shaped. The exact shape will depend on the characteristics of the stream flowing through it. Rivers with steep gradients, as in mountain ranges, produce steep walls and a bottom. Shallower slopes may produce broader and gentler valleys, but in the lowest stretch of a river, where it approaches its base level, it begins to deposit sediment and the valley bottom becomes a floodplain. [2]

2.Joint Formation

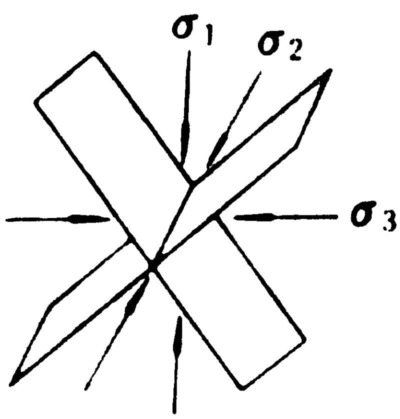


Fig.1 Three direction strength: $\sigma_1 > \sigma_2 > \sigma_3$

Joints form in solid, hard rock that is stretched such that its brittle strength is exceeded (the point at which it breaks). When this happens the rock fractures in a plane parallel to the maximum principal stress and perpendicular to the minimum principal stress (the direction in which the rock is being stretched). This leads to the development of a single sub-parallel joint set. Continued deformation may lead to development of one or more additional joint sets. The presence of the first set strongly affects the stress orientation in the rock layer, often causing subsequent sets to form at a high angle to the first set. [1]

Joint control of Valley creation: Formation of joint creates a relatively weak area which suffered more weathering than other parts. Along with joint planes, fluid promotes weathering rate of this area. Differential weathering forms prime Valley. The prime Valley make regional runoff gather to the valley, and speed up the further development of the valley.

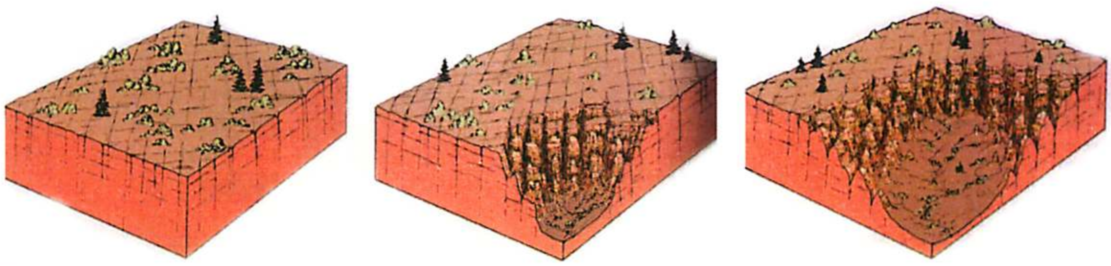


Fig.2 Development from Joint to Valley.

3.Valley on Mars and other planets

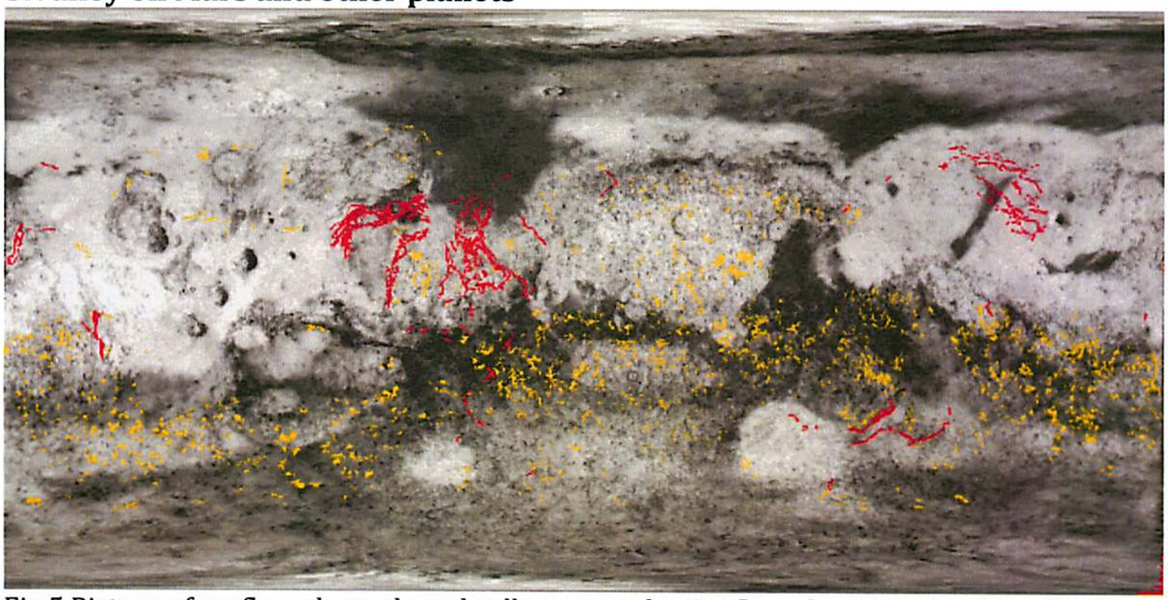


Fig.5 Picture of outflow channels and valley networks. Outflow channels are colored red, and the valley networks are yellow. [3]

The valley networks are present over almost half the Mars, mostly in the ancient heavily-cratered southern highlands. Based on our observations from orbit, Mars appears to be very dry. There is little water in the atmosphere and only a small amount of water ice in evidence on the surface. Yet the planet is covered with features that are best explained by the movement of water, either in catastrophic floods or the slow movement of groundwater. Whether that water was present early in the history of Mars and was lost to space over eons, or is still present in great underground deposits of ice and groundwater, is a question whose answer must be left for the future exploration of Mars.[3]

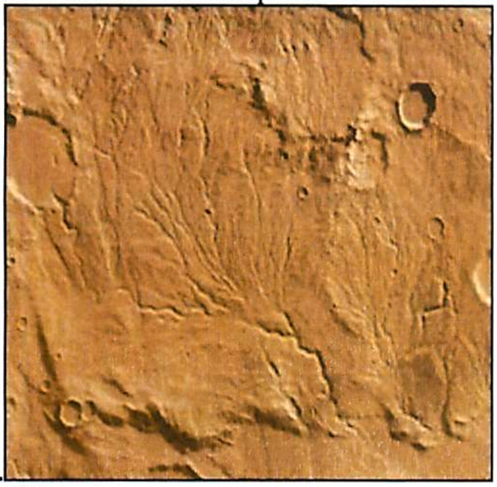
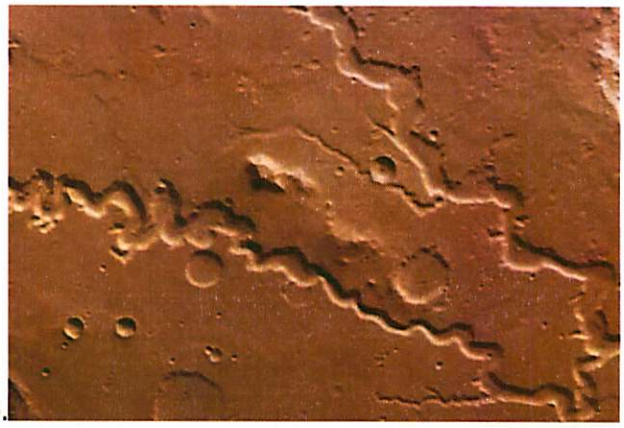
a.  b. 

Fig.6 Valley on Mars . (a). Valley Network (42°S,92°W)[4] . (b) Nanedi Valley in the Xanthe highland region [5] .

Discussion: In other planets and moons, they also have valleys. Some valleys on Venus and the Moon are related with magma erosion; many on Mercury and Mars are formed with water and some with magma erosion; on Europa, many are methane organics flowing in ice. Bedrocks could be rock or water ice, fluid could be water, magma or methane et al.. These valleys formation may be created by "fluid" interact with joint in "bedrock".

Reference:

[1] http://en.wikipedia.org/wiki/Joint_(geology)
[2] http://en.wikipedia.org/wiki/Valley
[3]http://www.msss.com/http/ps/channels/channels.html
[4]http://marsproject.niu.edu/
[5]http://www.dlr.de/mars/en/desktopdefault.aspx/tabid-4547/421_read-3082/

GRUSSIFICATION OF GRANITE AND SPHEROIDAL WEATHERING E. I. Schaefer

Introduction: The mechanical and modest chemical alteration of granite (and some other rocks) *in situ* can produce a mass of coarse, angular grains, called grus, as well as spheroidal boulders.

Granite Formation: Granite is a felsic, intrusive igneous rock of 20-60% quartz and 10-65% alkali feldspar [*Winter*, 2001]. This composition often gives granite a light-toned, pinkish or grayish color [**Fig. 1a**].

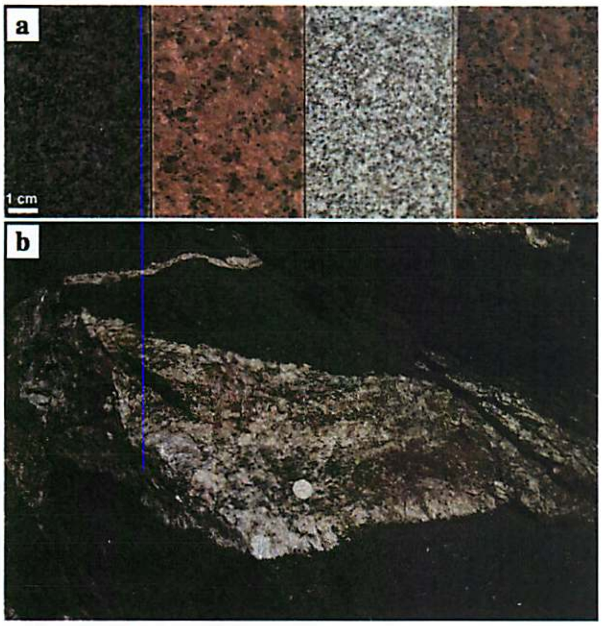


Fig. 1: (a) Various granites. (b) A granite vein formed by partial melting of surrounding mafic rock.

Granite is the most common rock in the upper crust of Earth's continents, constituting ~86 vol.% [*Bonin et al.*, 2002]. Since it is intrusive, it forms at depth from slowly-cooling, injected magmas. The highly felsic composition of granite requires that its parent magma must have formed by some combination of [*Winter*, 2001]

- whole-rock melting of similarly felsic rock (for example, a felsic sandstone)
- partial melting of more mafic rock [**Fig. 1b**]
- evolution from an originally more mafic composition by, for example, fractional crystallization

Partial melting and fractional crystallization are possible because felsic minerals are stable at lower temperatures in Bowen's reaction series [**Fig. 2**] than mafic minerals. Most granite is probably derived from crustal material [*Winter*, 2001].

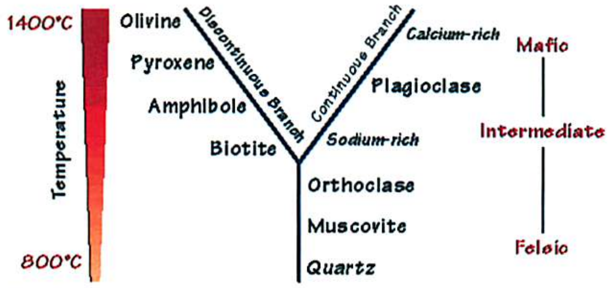


Fig. 2: Bowen's reaction series

Abundant granite is produced on Earth because its compositions (likes those of basalt) lie at thermal minima [*Bonin et al.*, 2002]. However, water greatly reduces these thermal minima, so wet systems produce granite much more efficiently and thus in larger volumes [*Bonin et al.*, 2002]. This partially explains the lack of large granitic provinces on planetary bodies other than Earth, but granite in smaller volumes is expected on Mars and Venus and is confirmed for the Moon and some meteorites [*Bonin et al.*, 2002].

Grus: "Grus" describes the coarse, angular grains that result from *in situ* physical weathering of crystalline rock, most commonly granite, combined with modest chemical weathering [**Fig. 3**] [e.g., *Migoń*, 1997]. With greater chemical weathering, significant clay is produced.

Unfortunately, "grus" is not a genetic term, since it describes both the products of weathering in the shallow subsurface and those of (typically much deeper) hydrothermal processes [*Migoń and Thomas*, 2002]. Worse yet, differing and sometimes conflicting definitions can be found in the literature [see *Migoń*, 1997]. For the purpose of field identification, a simple definition [*Migoń*, 1997] is

- sand + gravel ≥ 75%
- clay < 10%

Fig. 3: Grus formation sequence (in granite).

Since any feldspar in the parent rock will convert to clay *minerals* with sufficient chemical weathering, the upper limit on clay-*sized* particles is a proxy for degree of chemical alteration. Thus, in some sense, grus formation requires physical weathering to outpace chemical weathering. This is often facilitated by

- the presence of microfractures in the fresh parent rock [**Fig. 4a**] and/or
- early expansive alteration of biotite mica, causing interlayer splits [**Fig. 4b**] [*Migoń and Thomas*, 2002].

In both cases, the physical weakening promotes early disaggregation of the parent rock—grussification. The common formation of the microfractures by hydrofracturing explains part of the genetic ambiguity of grus [*Migoń and Thomas*, 2002].

A large body of work examines the climatic context of grus formation, often ascribing it to "arid and semiarid settings" [*Ritter et al.*, 2002], presumably to minimize alteration to clay. However, based on a survey of the literature, *Migoń* [1997] suggests that the problem is degenerate, depending instead on a balance of environmental factors rather than any one climate.

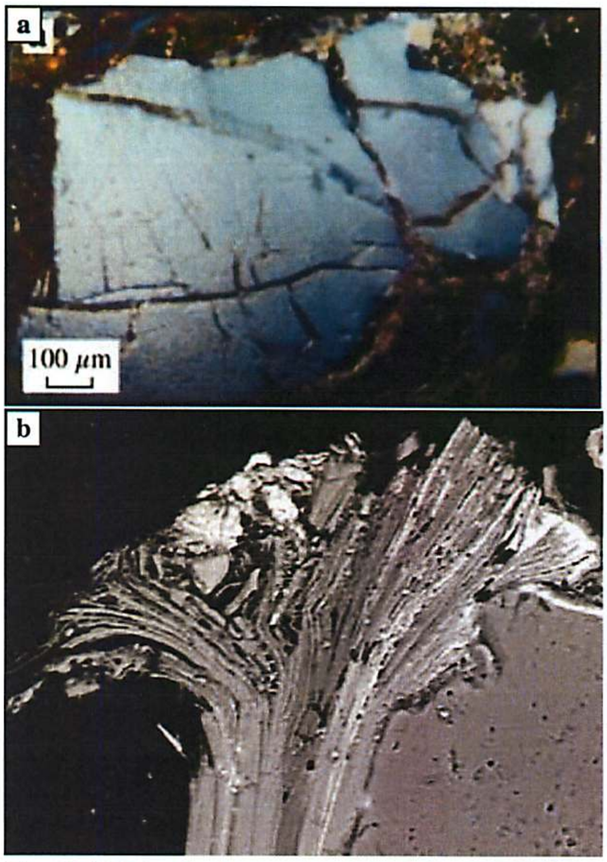


Fig. 4: (a) Microfractures in weathered granite. (b) Splitting of biotite layers by expansion due to hydration and oxidation.

Spheroidal Weathering: "Spheroidal weathering" is identified by its products: rounded corestones (which need not be truly spheroidal) completely surrounded by concentric shells and/or color bands [**Fig. 5**] [*Ollier*, 1971]. It occurs most commonly in granite and basalt, but it has also been observed in a wide variety of other lithologies, including metamorphic rocks and sandstone [see *Fletcher et al.*, 2006].

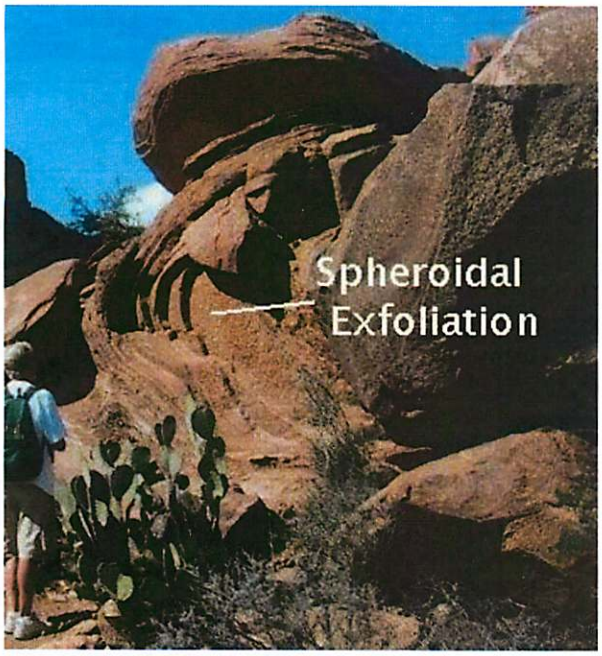


Fig. 5: Note how concentric spheroidal weathering yields spheroidal boulders.

Spheroidal weathering thus refers to any processes which may produce appropriate products, and a myriad of hypothesized processes have been proposed [see *Ollier*, 1971]. Most of these [see *Ollier*, 1971] agree that spheroidal weathering

- occurs in the subsurface, since it is unlikely that subaerial and subsurface weathering could be so balanced as to form the required uniform, enveloping geometry, and deeply buried spheroidal weathering products have been observed
- is facilitated by preferential weathering of corners, since their surface area/volume ratio is not minimized

Additionally, any specific mechanisms must explain [see *Ollier*, 1971]:

- how *multiple* concentric patterns form
- why concentric layers are typically uniform in thickness for a given site

Two proposed mechanisms are [see *Ollier*, 1971]:

- pressure release during unloading
    - known to cause curved surfaces at larger scales in similar rock types (exfoliation)
    - strongly suggested at one unusual site, but in general, many corestones are never deeply buried or are observed while still very deeply buried
- Liesegang hypothesis
    - possibly related Liesegang rings are periodic zones of precipitation formed by diffusion of solutions; periodicity results from alternation between diffusion and supersaturation/ nucleation
    - periodicity is consistent with concentric geometry, but Liesegang rings are not as regularly spaced or shaped
    - spheroidal weathering bands, like Liesegang rings, exhibit chemical alternation between enrichment and depletion
    - concentric cracking is not associated with Liesegang rings, but limited parting is

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Metamorphic Rocks

Corwin Atwood-Stone

Formation of Metamorphoic Rocks

-Metamorphic rocks form by the alteration of prexisting rocks, sedimentary, igneous and even other metamorphic rocks.
-These alterations occur by the the application of: Heat, Pressure Time and sometimes the presence of fluids
-The fluids are important as they are able to add and remove minerals from the exsisting rocks
-Generally this occurs by one of two major processes
1: Contact Metamorphism
  -Contact of intrusive magmas with other rocks applies considerable heat and pressure to those rocks, as well as introducing considerable amounts of chemically rich fluid.
  -This combination produces a fairly narrow zone of intence metamorphism in the rocks sorrounding the magma
2: Regional Metamorphism
  -This involves the metamorphosing of much larger regions of rock the contact metamorphism.
  -In this case the pressures and heat are due to orogenies or deep burial of the metamorphosing rock.
-There are two major classes of metamorphic rocks by texture, Foliated [Fig. 13] and Nonfoliated [Fig. 12].

Foliated Metamorphic Rocks

-Foliations are layers within the rock formed by preferential orientation of certain minerals like mica.
-This preferential orientation occurs when there is a unidirectional stress field.
-Different types of foliated rocks form at different metamorphic grades (levels of T and P).
- At the lowest grade a rock called Slate [Fig. 1] can form from shale. Slate is composed of microscopic platy minerals, largely quartz and mica, and has large horizontal clevage planes.
-At a slightly higher grade the rock Phyllite [Fig. 2] will form. Phyllite is composed of just barely visible crystals. The foliations are often wrinkled or wavy.
-Medium grade metamorphism will result in a class of rocks known as Schists [Fig. 3] which have larger grains and whose foliation is very irregular. Schists are defined by their mineral assemblage and are notable for containing large crystal inclusions called porphyroblasts [Fig. 4].
-The highest grade of metamorphism produces the banded rock Gneiss [Fig. 5]. The different bands in a gneiss will be dominated by different minerals, gennerally mafic and felsic, producing the different colors. Unlike the previous rocks, gneisses are less dominated by platy minerals like micas.
-Further metamorphism results in Migmatites which are transitional back to igneous rocks.


Fig 1: Slate

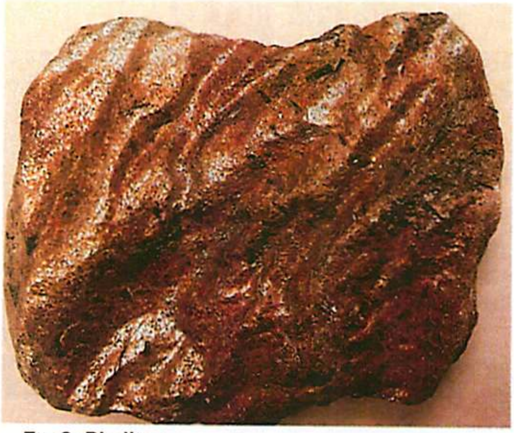
Fig 2: Phyllite


Fig 3: Schist

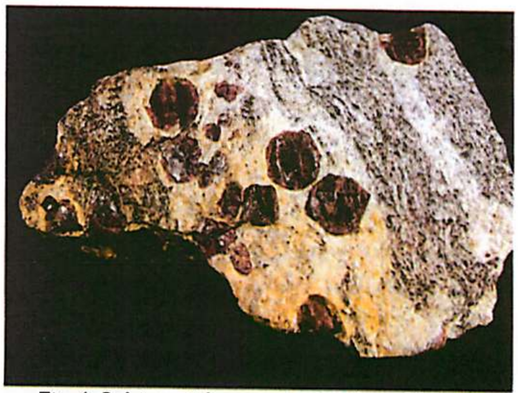
Fig 4: Schist with garnet porphyroblasts

Nonfoliated Metamorphoic Rocks

-Nonfoliated metamorphic rocks form when there is not unideriectional stress, or if the original rock lacks platy minerals.

-The different types of nonfoliated rocks generally come from very specific parent rocks, unlike foliated rocks where different precursor rocks with similar minerology may produce the same metamorphic rock.

-Metamorphism of sandstone will produce the rock Quartzite [Fig. 6], which appears granular and crystaline. Fractures through this rock will break through the grains and not around them as in sandstone. Additionally this is a very tough rock.

-Alteration of limestones will produce the familiar rock Marble [Fig. 7], which has its streaked and banded pattern due to impurities. Another process called metasomatism wherein limestone and quartz are altered together produces the rock Skarn [Fig. 8] which is often much more brightly colored then the related marble.

-Basalts and other mafic rocks are often altered in to a dull, slightly green rock known as Greenstone [Fig. 9], though depending on metamorphic grade these rocks can also become Serpentine.

-Another category of nonfoliated rocks are Hornfels [Fig. 10], which form in the highest grade settings, often in contact metamorphism. This is a dull dark rock type that can form from a variety of precursor rocks.

-Some supprising rocks are considered metamorphic, such as Anthracite Coal [Fig. 11] which forms from bituminous coat. Another interesting metamorphic rock is graphite.

Planetary Conection

-On Mars recent evidence has been found using CRISM for low grade metamorphism from the presence of certain minerals, especially phenite, which only form under metamorphic conditions (Ehlmann et al. 2011). While there is as yet no evidence for high-grade, on would at least expect it from contact metamorphism.

-On Venus there is no definite evidence of metamorphism, though it seems likely. One interesting idea from Spencer et al. 2001 is that Artemis Corona has a metamorphic core complex at its center.

-A question I have is what could metamorphism look like on Titan and other icy Satellites.

Images for this paper come from Ossian, C.R. (2000), Insights: A labratory manual for physical & historical geology.

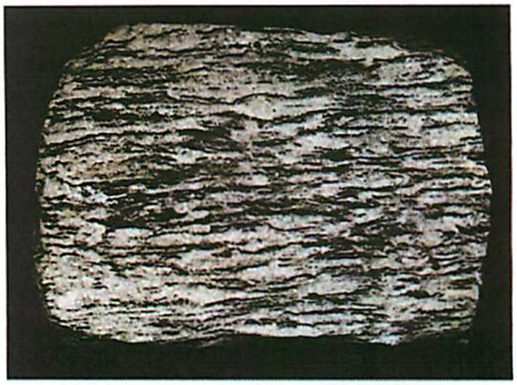
Fig 5: Gneiss

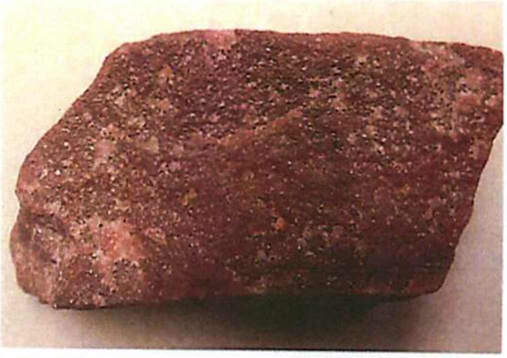
Fig 6: Quartzite

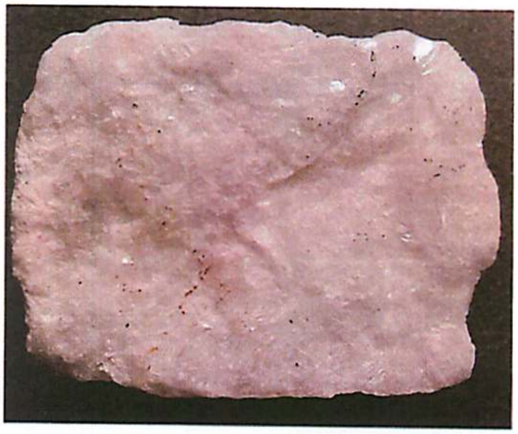
Fig 7: Marble


Fig 8: Skarn

Fig 9: GreenStone

Fig 10: Hornfels

Metamorphic Rock	Comments
QUARTZITE	Composed of interlocking quartz grains
STRETCHED-PEBBLE CONGLOMERATE	Original pebbles distinguishable, but strongly deformed
GREENSTONE	Composed of epidote and chlorite; green
AMPHIBOLITE	Composed of amphibole and plagioclase; coarse-grained
HORNFELS	Composed of pyroxene and plagioclase; fine-grained
HORNFELS	Composed of quartz and plagioclase; fine-grained
MARBLE	Composed of interlocking calcite or dolomite grains
SKARN	Composed of calcite and added minerals; multicolored
SERPENTINITE	Composed chiefly of serpentine; greens
SOAPSTONE	Composed chiefly of talc; soapy feel
ANTHRACITE COAL	Bright, hard coal; breaks with conchoidal fracture
GRAPHITE	Soft, dark gray, with greasy feel

Fig 12: Chart of some nonfoliated metamorphic rocks

Fig 11: Anthracite Coal

Increasing Grade of Metamorphism ↓

Grain-size Class and Diameter	Rock Names		Comments
Microscopic, very fine-grained	SLATE		Slaty cleavage well developed
Fine-grained	PHYLLITE		Phyllitic texture well developed; silky, shiny luster
Coarse-grained, macroscopic, mostly micaceous minerals or prismatic crystals; often with porphyroblasts	SCHIST	MUSCOVITE SCHIST CHLORITE SCHIST BIOTITE SCHIST TOURMALINE SCHIST GARNET SCHIST STAUROLITE SCHIST KYANITE SCHIST SILLIMANITE SCHIST AMPHIBOLE SCHIST	Types of schist recognized on the basis of mineral content.
Coarse-grained; mostly nonmicaceous minerals	GNEISS		Well-developed color banding due to alternating layers of different minerals.

Fig 13: Chart of foliated metamorphic rocks

Mylonite and Cataclastic Deposits

Cecilia Leung

I. CATACLASTIC vs. MYLONITIC METAMORPHISM:

- Both cataclasites and mylonites are metamorphic rocks resulting from mechanical deformation
- Downward dip of detachment fault produces:
  1. Cataclasites by brittle shear
  2. Mylonites by ductile shear

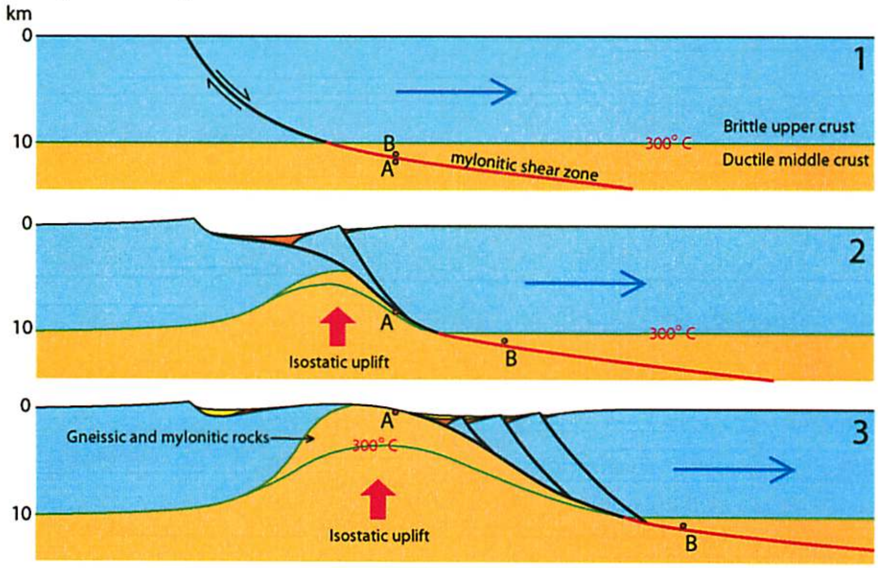

Fig. 1 Idealized cross-sectional evolution of a metamorphic core complex [Ref. 1]

Cataclasite:

- Progressive fracturing during brittle faulting (cataclasis) continues until the distribution of clast sizes allows clasts to slide past each other, but without high enough frictional stresses to further fracture the rock significantly
- Consists of angular clasts set in a finer-grained matrix:
  protocataclasite (<50% matrix), mescataclasite (50-90%), ultracataclasite (>90%)

Mylonite:

- Produced past the brittle-ductile transition in the middle crust where T> 300°C
- Plastic deformation pulverize rock into a fine-grain
- Layers and streaks drawn out by ductile shear

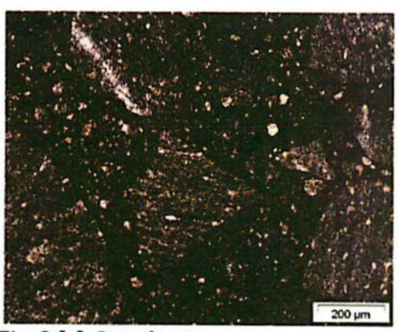

Fig. 2 [a] Cataclasite

[b] Mylonite

[c] S-C Mylonite at Windy Point

II. METAMORPHIC CORE COMPLEX IN THE TUCSON REGION:

A. Windy Point Shear Zone

- All rocks visible along Catalina Highway make up footwall block of Catalina detachment fault
- Classic S-C mylonitic fabric at Windy Point
    - S-(flattening) planes → long dimension of feldspar porphyroclasts
    - C-(shear) slanted planes → spaced at ~3mm. Orientated parallel to shear zone boundaries
    - Intersection of S and C fabrics indicate sense of shear: Top-southwest
- Protolith: 2-mica (muscovite and biotite) garnet-bearing granite

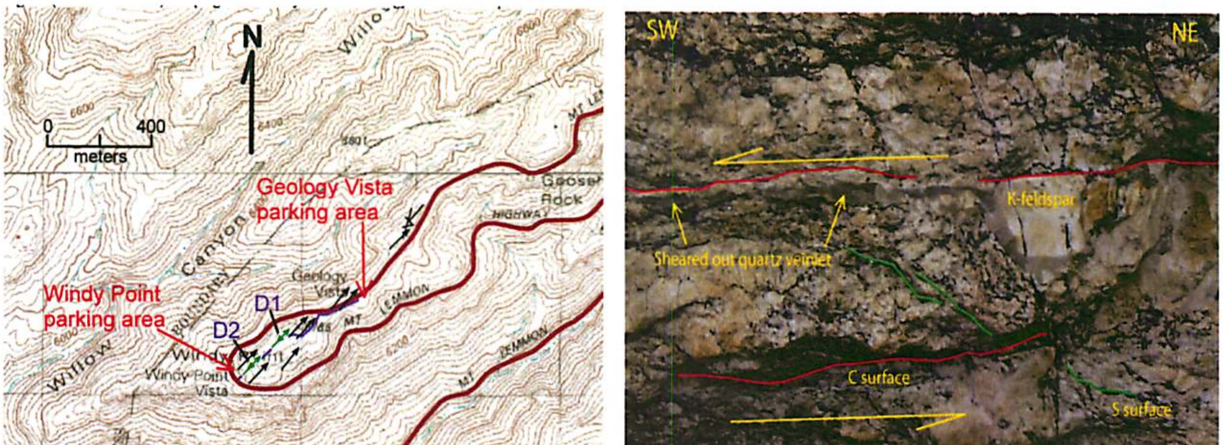

Fig. 3 (Left) Map of Windy Point along Catalina Hwy. Green arrows = top-SW shear indicators [1]
(Right) S-C shear-sence indicator and sheared-out quartz veinlet on SE side of rock at location D1. [1]

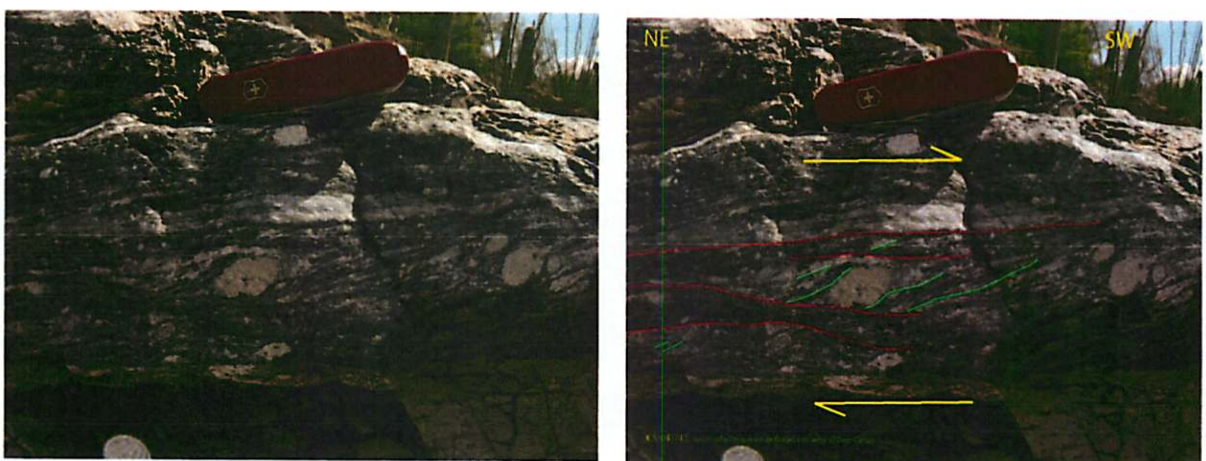

Fig. 4 S-C Mylonite S-surface (flattening)= green. C-surfaces (shearing) = red. Note the white rotated porphyroclasts with development of asymmetric tails [1]

B. Rincon Mountains: Salcido Ranch

- Shearing and detachment faulting along Catalina brittle-ductile shear zone
- Catalina detachment fault oriented E-W with 10-20°S dip
- Separates upper plate rocks from underlying brown/gray cataclasites

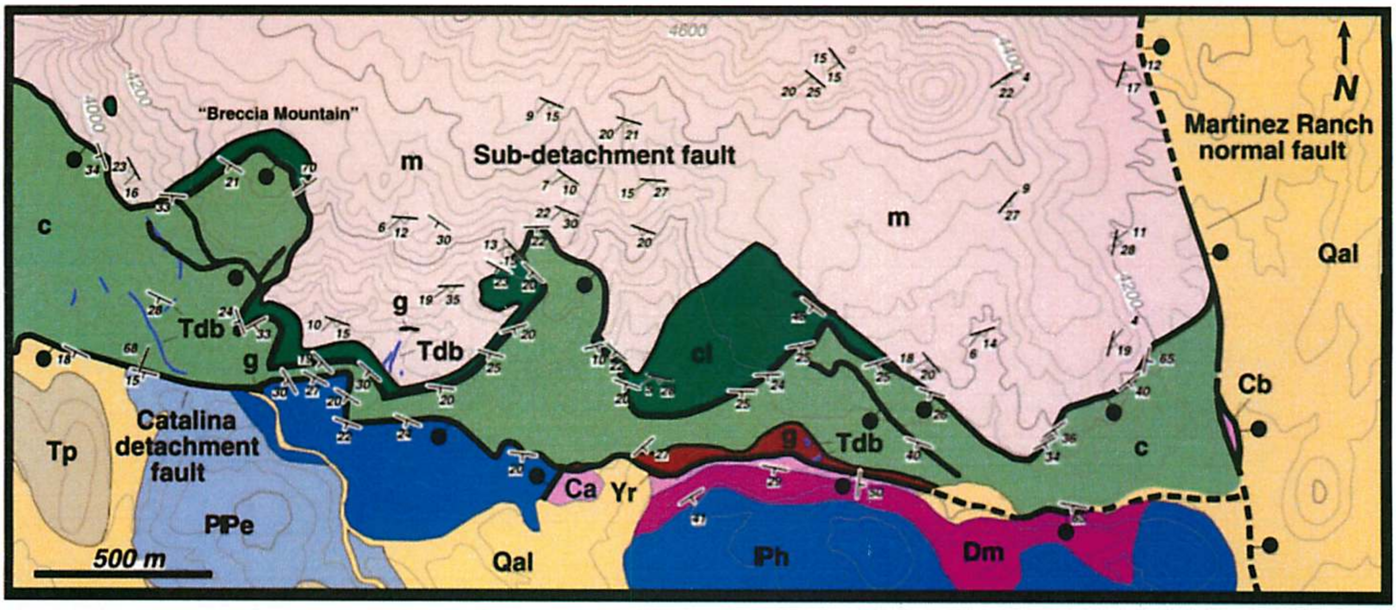

Fig. 5 Geologic map of Metamorphic core complex at Salcito Ranch [2]
Fault-rock: c: cataclasite, cl: cataclasite beneath sub-detachment, m: mylonite, g: gouge
Rock units: Yr, Cb, Ca, Dm, Ph, PPe, Tp, Tdb, Qal

Cataclasite:
- above subdetachment fault = coarse grained
- beneath subdetachment fault= fine-grained

Base of zone of cataclastic deformation marked by sharp transition from cataclastic deformation to mylonitic deformation

Mylonite:
- Exposed Mylonites, ultramylonites, and microbrecciated mylonites
- fine-grained matrix has strongly foliated & lineated crystal-plastic textures
- Feldspar porphyroclasts typically <5mm
- Protolith: Eocene Wilderness Suite Granite (quartz monzonite)

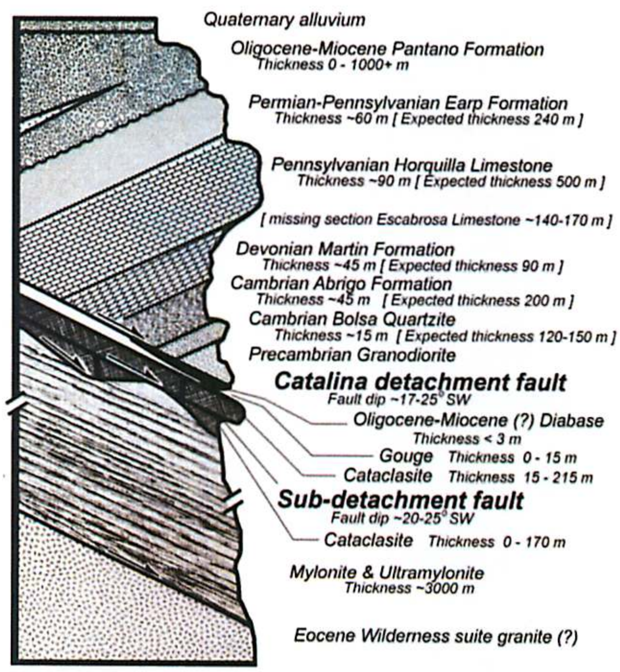

Fig. 6 Stratigraphy and fault-rocks at Salcito Ranch [2]

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[2] G.H. Davis et al. Structural-Geologic Map Relationships in the Salcita Ranch Area, Rincon Mountains, S AZ. March 2011
[3] http://geology.about.com/ & http://en.wikipedia.org/→ Cataclasite, Mylonite

Detachment-limited erosion in mountain channels

Jamie Molaro

What is detachment-limited erosion?

When the transport of soil is limited by the environment's ability to produce that soil it is called detachment- (or weathering-) limited erosion.

In wet, humid environments, soil is produced very quickly due to the abundance water available for fluvial, chemical, and biological weathering processes. In these environments we have transport-limited erosion, where the modification of the landscape is limited by how quickly the soil can be moved. There is a shift from transport- to detachment-limited erosion as you move away from the equator towards the desert belts. In dry environments, the build up of soil is prevented because weathering occurs very slowly. Since there are processes at work to transport material (Aeolian and fluvial processes, bioturbation), it is often eroded very quickly after it's created resulting in bare, rocky landscapes.

Ok, but what does that have to do with rivers?

In the context of fluvial processes, both external environment (e.g. desert vs. rainforest) and gradient are controls on the erosional regime of a particular landscape. In a process like bedrock incision, the stream power (as well as the composition and strength of the bedrock) determines erosion rates. The stream power of a channel is proportional to the slope_gradient*fluid_discharge (Ritter et al. 2006).

Rivers in dry environments, and/or with high stream power	= detachment-limited
Rivers in wet environments and/or with low stream power	= transport-limited

High altitude, bedrock channels typically have steep slopes, and therefore high energy, and are capable of moving significantly more sediment than is available for transport (Ritter et al. 2006). This places them in the detachment-limited erosional regime. Due to their high energy, any material that is detached from the bedrock is moved downstream very quickly. They are non-alluvial channels that contain very little sediment in the water. As you move lower in the drainage basin, gradients become less steep, allowing material to be deposited on the channel floors. Additionally, more soil begins to be deposited along the channels banks (both from the river and via overland flow processes). This moves the channels towards a transport-limited regime. Very low altitude, low energy river channels tend to be full of sediment, and meander easily due to the higher erodability of the channel banks.

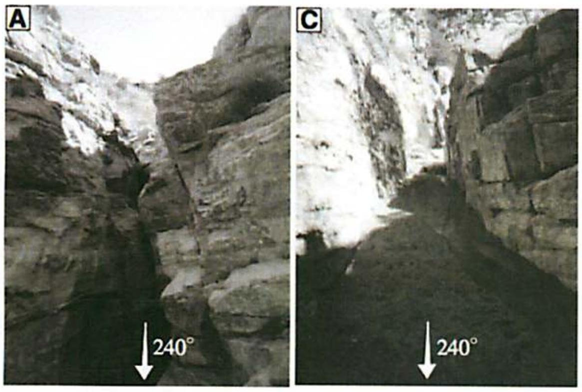
Channel formation and other fluvial processes are, obviously, limited by the amount of rain the landscape gets. Desert environments may not receive a lot of rain, but often when they do it floods. A large amount of water filling the channels at once will make weathering and eroding material relatively efficient during a single storm, however the frequency of rainstorms will cause the landscape to be modified very slowly. Alterations in channel form are noticeable only over periods of decades or centuries. For this reason, erosion rates in bedrock channels are typically estimated using numerical models (e.g. Howard, 1994).

What processes operate in a detachment-limited environment?

The primary processes involved in the soil production and erosion in bedrock channels are abrasion, plucking, cavitation, and some chemical processes (Richardson & Carling 2005). The dominant weathering processes is determined by the composition and structure of the bedrock, as well as the energy of the flow.

Abrasion: Slow incremental wearing away of bedrock from the sediment available in flowing water to impact and grind away material. The impacting particles may be suspended in the water or carried as bedload. The size, density, and velocity of the impactors determine how much material is removed from the bedrock. This process smooths and polishes channel boundaries, as well as breaks down entrained impactors causing downstream fining.

Plucking: The entrainment and transport of bedrock blocks from the channel boundaries (Baker 2009). Local vortices in the water cause pressure lows that pluck pieces from the bedrock. The size of the blocks is determined by bedrock fractures, joints, or bedding planes, as well as how high energy the flow is. Prior to removal, blocks go through a period of preparation where their cracks are widened and they become loosened by hydraulic forces, sand wedging, abrasion, etc. Eventually lift and drag forces entrain the block in the water and transport it downstream (Richardson & Carling 2005). It requires high energy, deep flows with discharge rates of $\sim 10^7$ m^3/s, which is huge (the Mississippi has only $\sim 10^4$ m^3/s)!

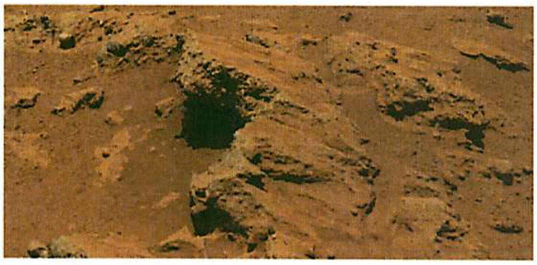


This process is visible in the Upper Soldier Creek area where a stream has cut a slot canyon into the bedrock. In this area, channels of all sizes exploit steeply dipping joint sets during fluvial incision, causing them to become preferentially aligned along those joint sets. The larger drainage architecture is the result of a combination of joint exploitation and tectonic tilting mechanisms, where tectonic uplift caused the formation of knickpoints which migrate upstream from bedrock plucking (Pelletier et al. 2009).

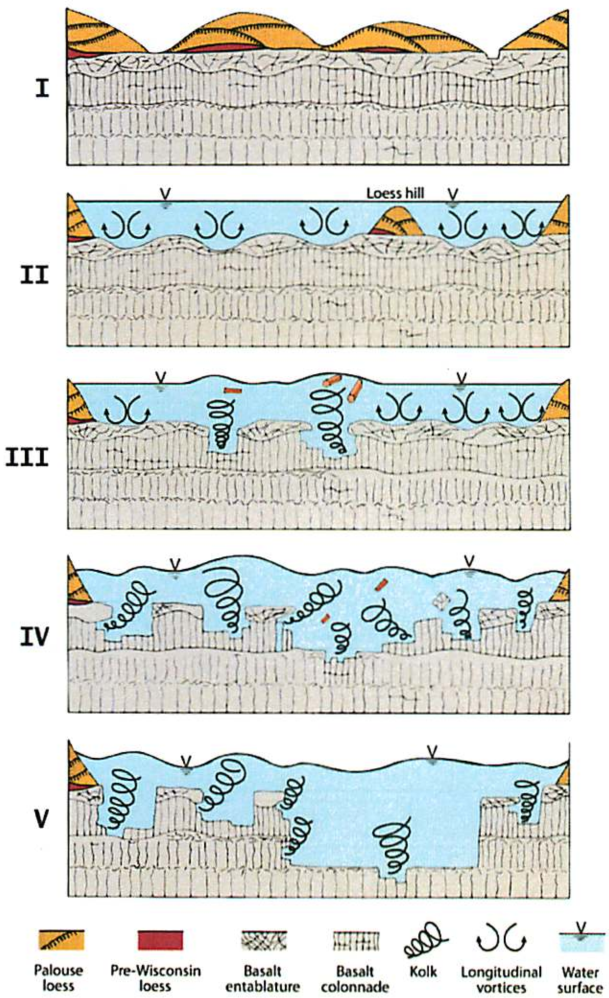
Cavitation: The formation and implosion of bubbles in water. The implosion of bubbles near a surface generates shock waves that can weaken rock and roughen the surface. This process also typically only occurs in very high energy flows (e.g. flows through dams).

Planetary Connection

The Cassini–Huygens spacecraft imaged what appear to be drainage basins and fluvial channels on Titan's surface. Burr et al. (2006) estimated required flow depths and velocities for surficial flow of methane on Titan's surface to transport material. They found that non-cohesive material would move more easily than on Earth or Mars. Collins (2005) found that, despite the differences in the physical parameters that control fluvial erosion, bedrock incision rates on Titan are likely to be very similar to terrestrial rates. However, further research and data are needed to understand what kinds of weathering processes are active, as well as about the frequency or amount of rainfall on the surface, in order to get a better idea of what characterizes the channels we observe, and how they modify the landscape.



Recently, Curiosity found evidence of a streambed on Mars. While earlier evidence for the presence of water on Mars existed, Curiosity's images show never-before-seen ancient streambed gravels and conglomerate rocks. The more we find and study evidence of fluvial action on the ground, the better it will inform modeling and other studies of crater degradation and infilling. Forsberg-Taylor et al. (2004) found that degradation and infilling due to fluvial action was consistent with observations of heavily crated areas of Mars. Howard et al. (2007) found that even under arid conditions, drainage networks could form and crater basins could become integrated with each other through lateral erosion of their rims. In general, however, fluvial bedrock erosion would be more difficult on Mars, since the rocks are of similar composition as on Earth but the planet has lower gravity and therefore lower kinetic energy processes. We have a lot more data on Mars than on Titan, however since Mar's fluvial erosion happened so long ago, uncertainty about weather conditions as well as the presence of active surface processes today also makes it difficult to understand and characterize fluvial erosion in Mar's history.



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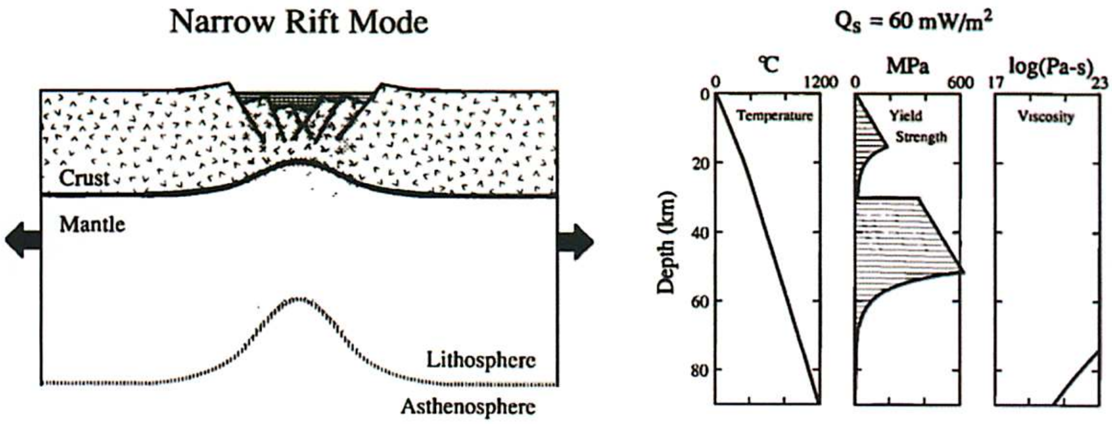
Metamorphic Core Complexes

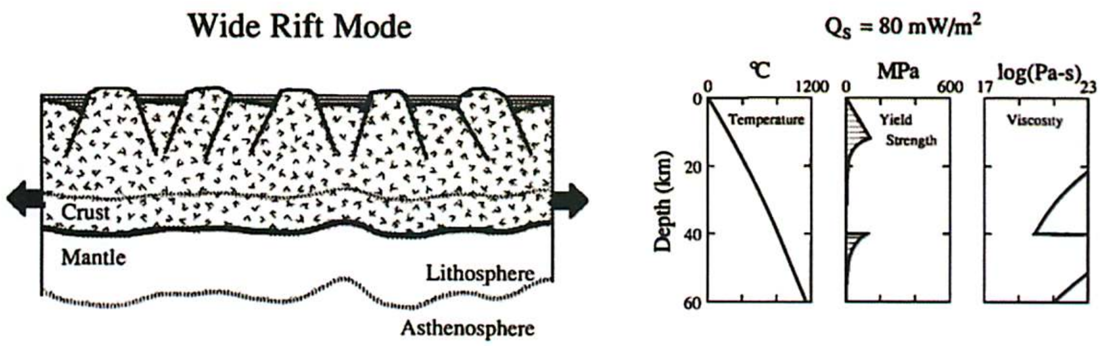
PTYS594 Field Guide, Circum-Tucson, Fall 2012 – James Tuttle Keane

1) Modes of Lithospheric Extension

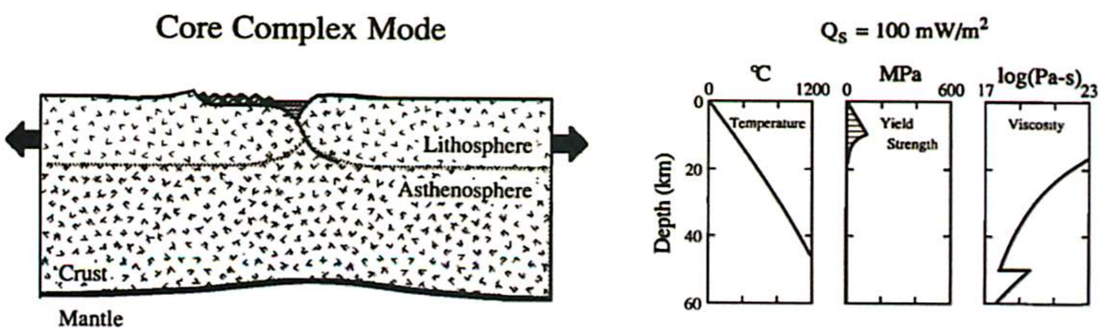
Narrow Rifts are narrow regions (<100 km wide) of intense normal faulting, characterized by large lateral gradients in crustal thickness and topography. Narrow rifts occur in regions of strong lithosphere, and low heat flows. The classical example is the East African Rift System.



Wide Rifts are wide regions (> 100's of km wide) of disperse normal faulting, with smaller lateral crustal thickness gradients and topography gradients compared to narrow rifts. Wide rifts occur in regions with thick crusts, and high heat flows – which result in a weak lithosphere. The classical example is the Basin and Range Province in the Western United States.

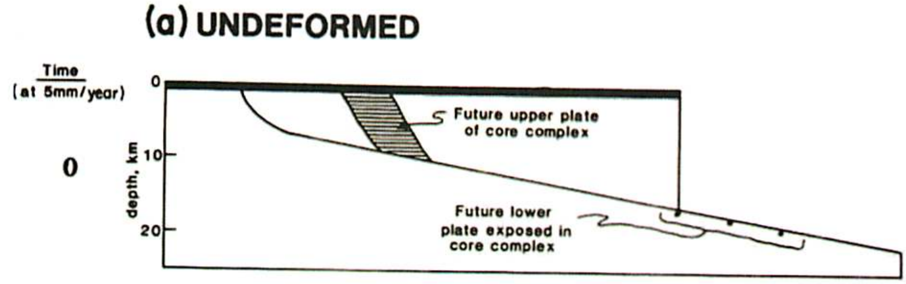


Metamorphic Core Complexes are a subtype of narrow rifts (<100 km wide), where extension has exposed high-grade metamorphic rocks from the lower crust. Core complexes lack strong topographic or crustal thickness gradients. Core complexes occur in regions with extremely high heat flows and strong lower crustal flow.

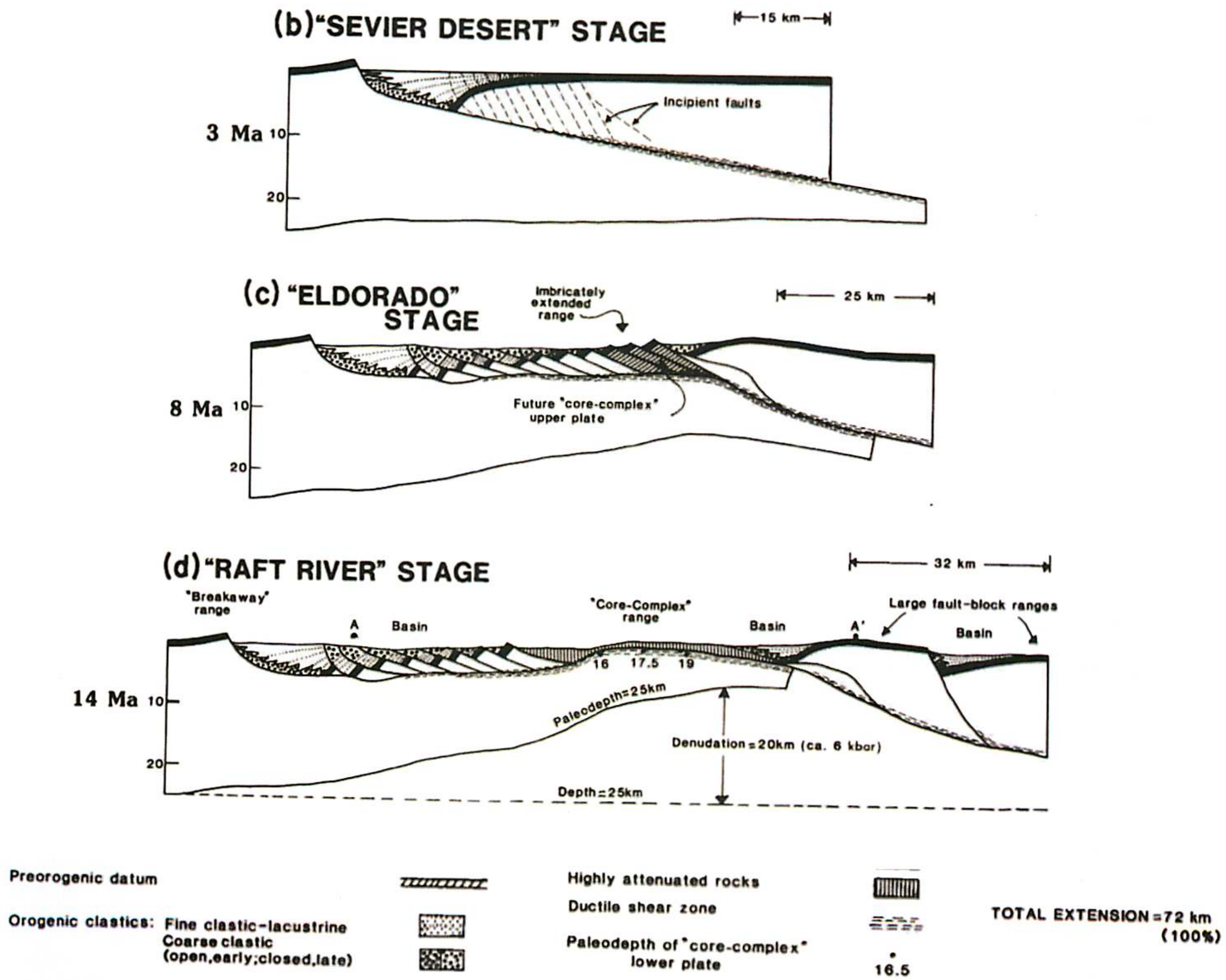


2) The Formation of Metamorphic Core Complexes

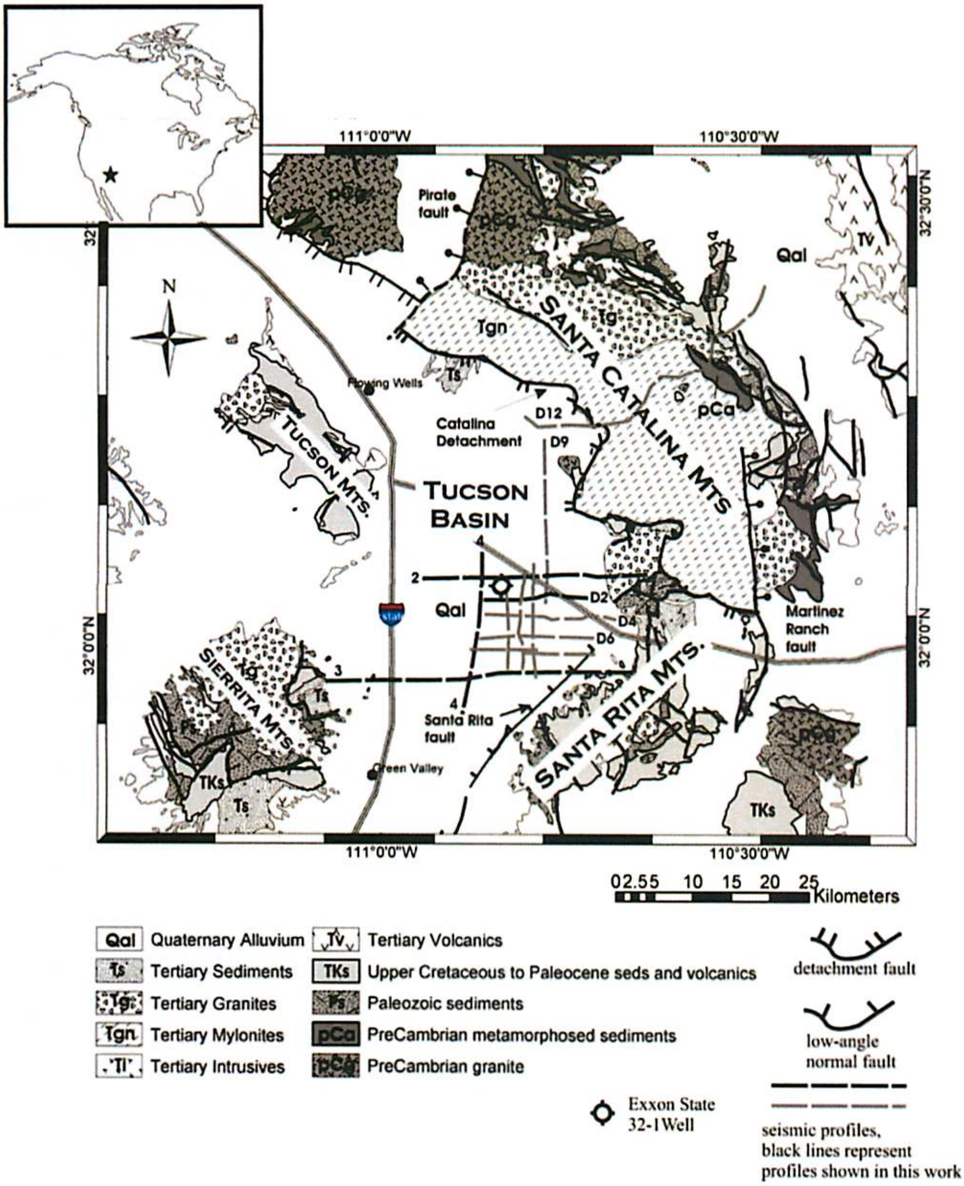
For a core complex to form, a low angle normal fault – sometimes called a detachment fault – cuts through the middle and lower crust, near the brittle-ductile transition depth. At this depth, the rocks are primarily metamorphic, in the greenschist or amphibolite facies.



As the region extends, blocks bounded by imbricate normal faults, are rotated exposing deeper crustal rocks. Unroofing of the upper levels triggers isostatic adjustment, preventing significant topographic variations. Lower crustal flow (not shown here), prevents thinning of the entire crust. Furthermore, decompression melting can occur and trigger extrusive and/or intrusive volcanism.



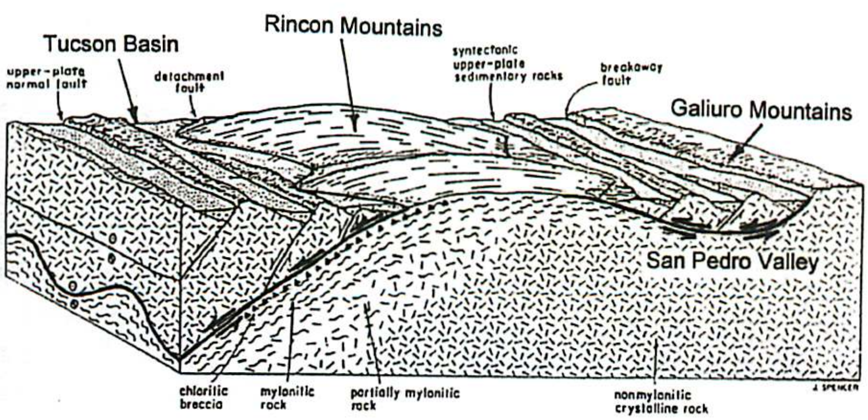
3) The Catalina-Rincon Core Complex



The Rincon-Catalina core complex forms a broad dome (the Catalina Mountains), of Teriary mylonitic gneiss and Precambrian granites.

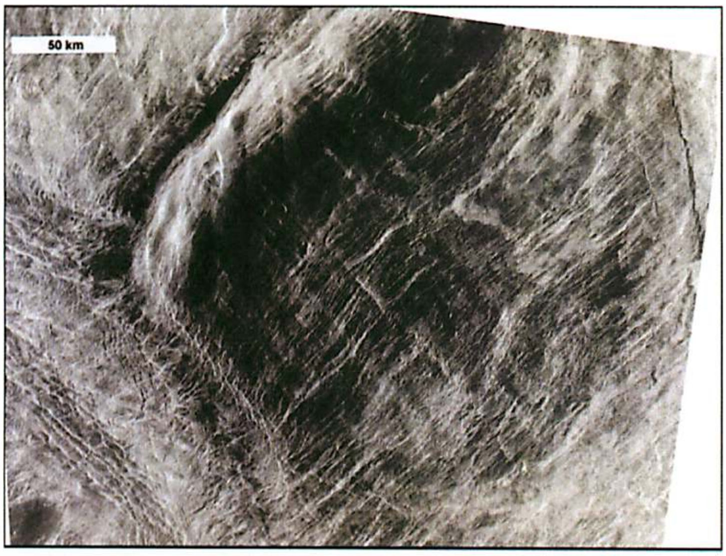
Mylonitic fabrics occur in a belt about 10 km wide along the Southwest flank of the Catalina mountains.

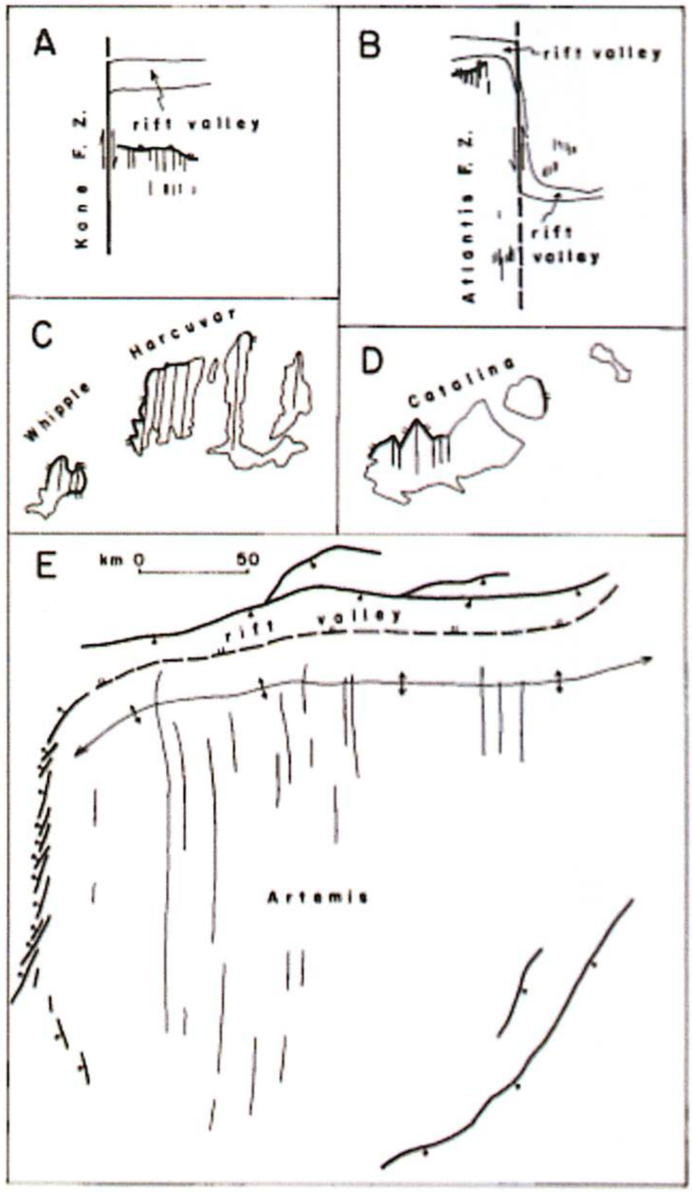
Down slope, there are younger, tilted cover blocks, which are are cut by numerous normal faults which merge down into a single detachment fault. The detachment fault itself can be identified in some locals by characteristic fault breccias.



4) Planetary Analogous

While wide/narrow rifts have been found on a large array of planets/moons (e.g. Venus, Europa, Ganymede, Enceladus), metamorphic core complexes have not been conclusively identified on other planets/moons. This likely owes to the lack of structural and stratigraphic data necessary to identify them. However, there are weaker morphological signatures of core complexes (asymmetric antiformal domes, with fault troughs, and slip-parallel grooves). Particular regions of Artemis Corona on Venus have these morphologies, and may represent core complexes. Venus is a very good candidate location anyway, owing to its presumably weak crust.





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Detachment Faulting and the Catalina Detachment Fault

Donna Viola

Detachment faulting is a type of extensional tectonics, usually associated with large displacements (on the order of tens of kilometers) at low dip angles. A detachment fault is typically the result of a sub-critical failure in shear zones near the brittle/ductile transition. This mechanism is depicted in Figure 1, where surface rock becomes brecciated and rock in the ductile region gets mylonitized.

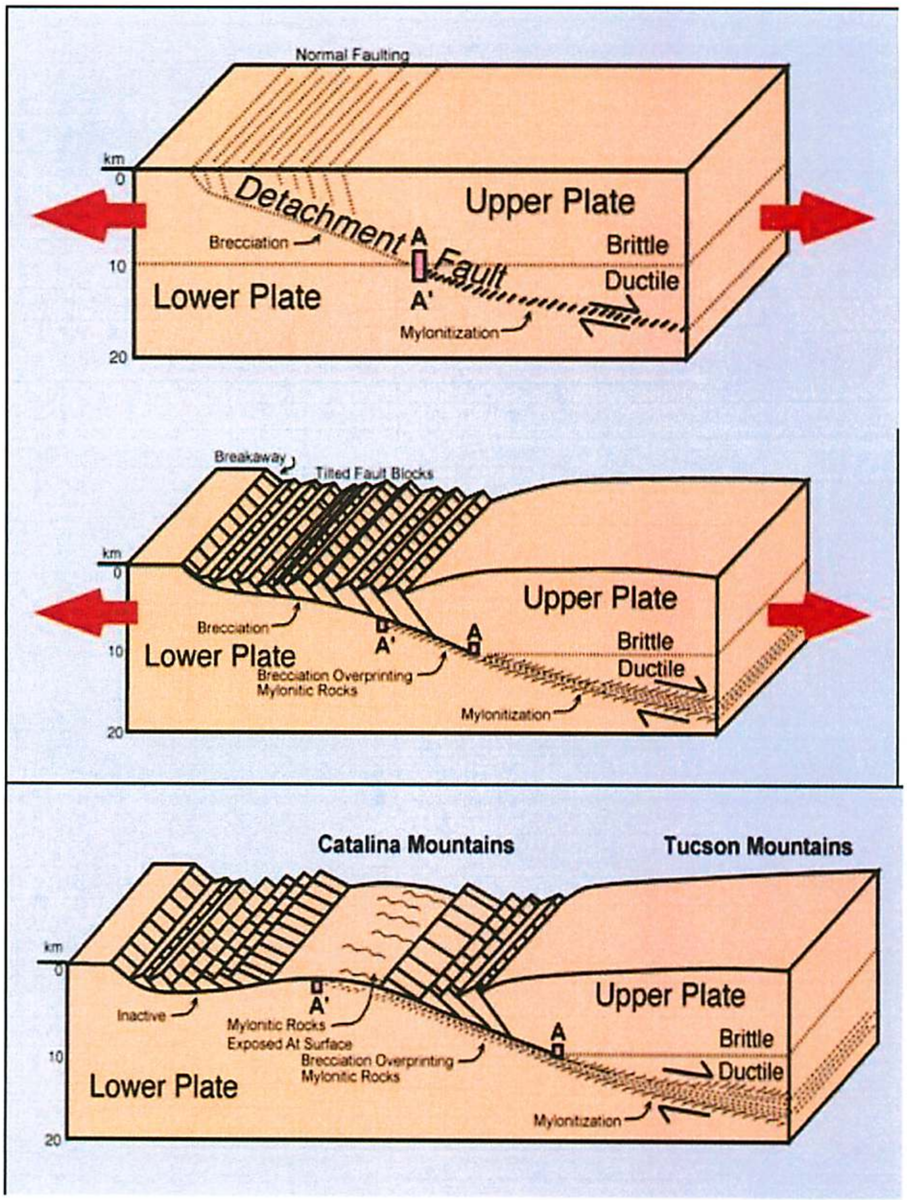

Figure 1: Mechanism of detachment faulting (top two panels) and the resulting orientation of the Catalina Mountains (bottom panel)

The Catalina Detachment Fault occurred about 20 million years ago, between the Oligocene and the Miocene. Figure 2 shows the present configuration of the plates involved in the detachment faulting event; note that the Catalina and Rincon Mountains were a part of the lower plate, and comprise the metamorphic core complex that was rapidly exhumed from beneath the Tucson basin (see also Figure 1, panel 3).

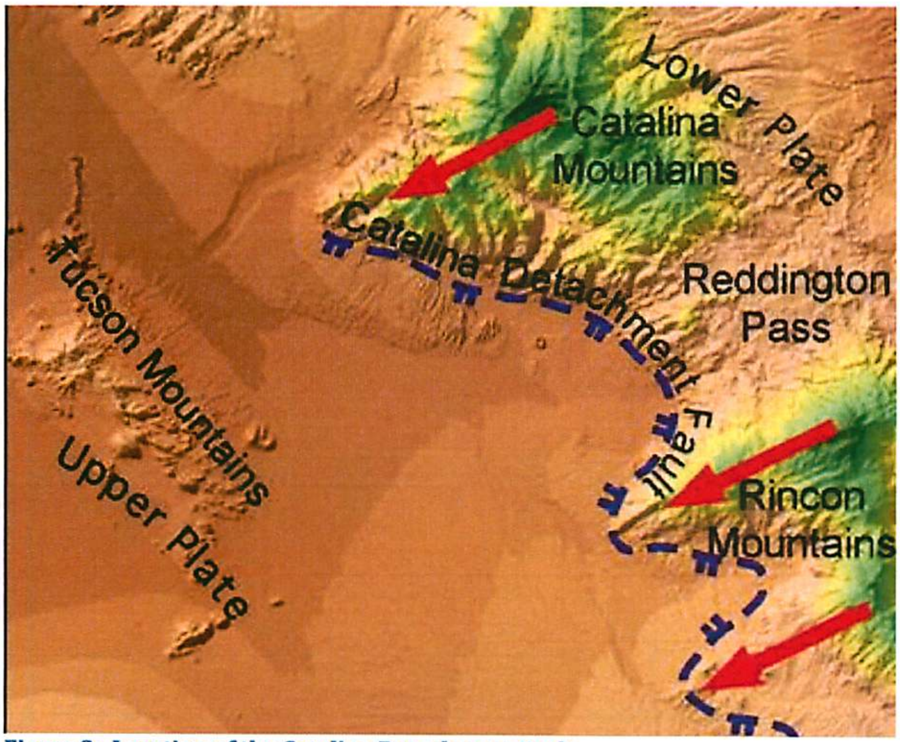

Figure 2: Location of the Catalina Detachment Fault.

Figure 3 is a geologic map, and offers another perspective of the Catalina Detachment Fault. Note the black arrows which indicate that the entire fault appears to have caused a total displacement of ~30 kilometers, as evidenced by blocks of the same material that was interrupted by the fault.

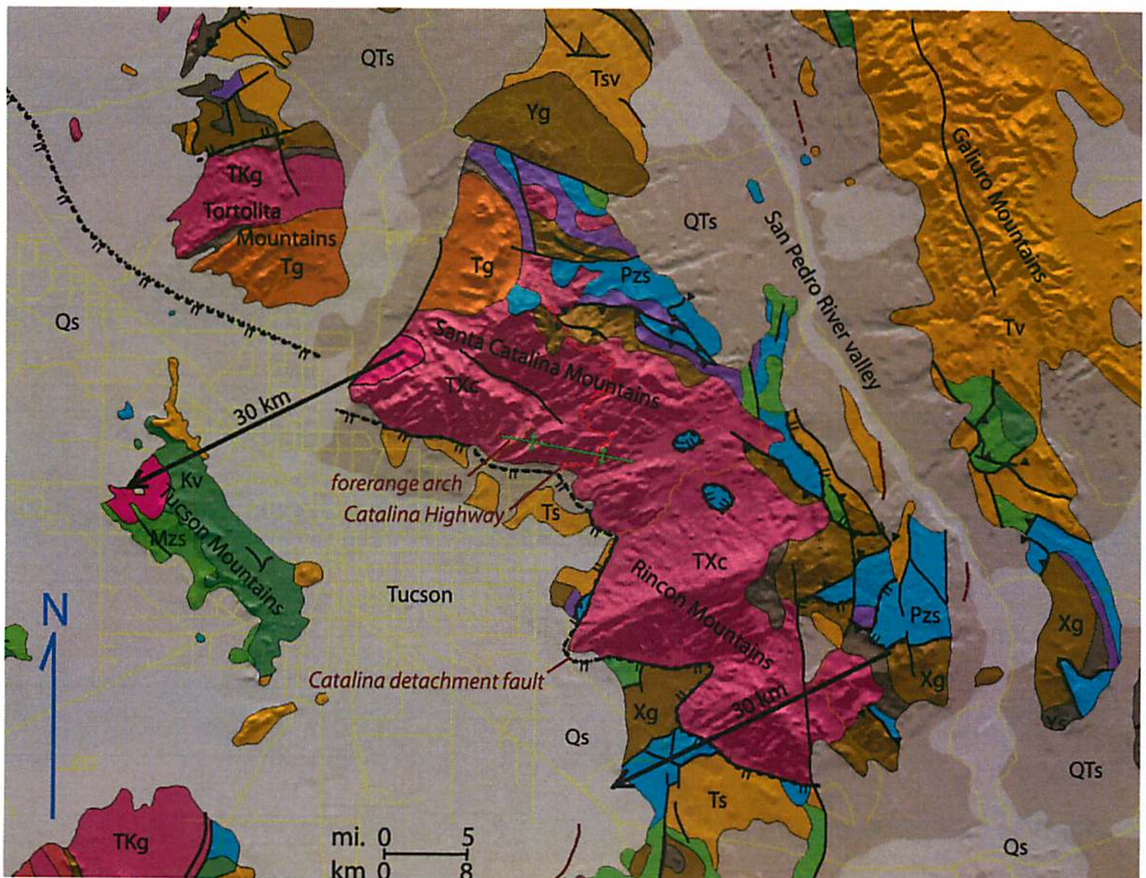

Figure 3: Geologic map of the Catalina and Rincon Mountains.

The upper plate rocks, above the detachment fault, include Precambrian and Paleozoic units, which typically show some evidence for internal deformation. Below the detachment fault, there are cataclastic rocks and mylonite which came from the brittle part of the shear zone. The detachment fault itself is apparent in ahighly resistant cataclastite ledge 1-2 meters thick. Figure 4 shows a cross-section of the layers above and below the Catalina Detachment Fault.

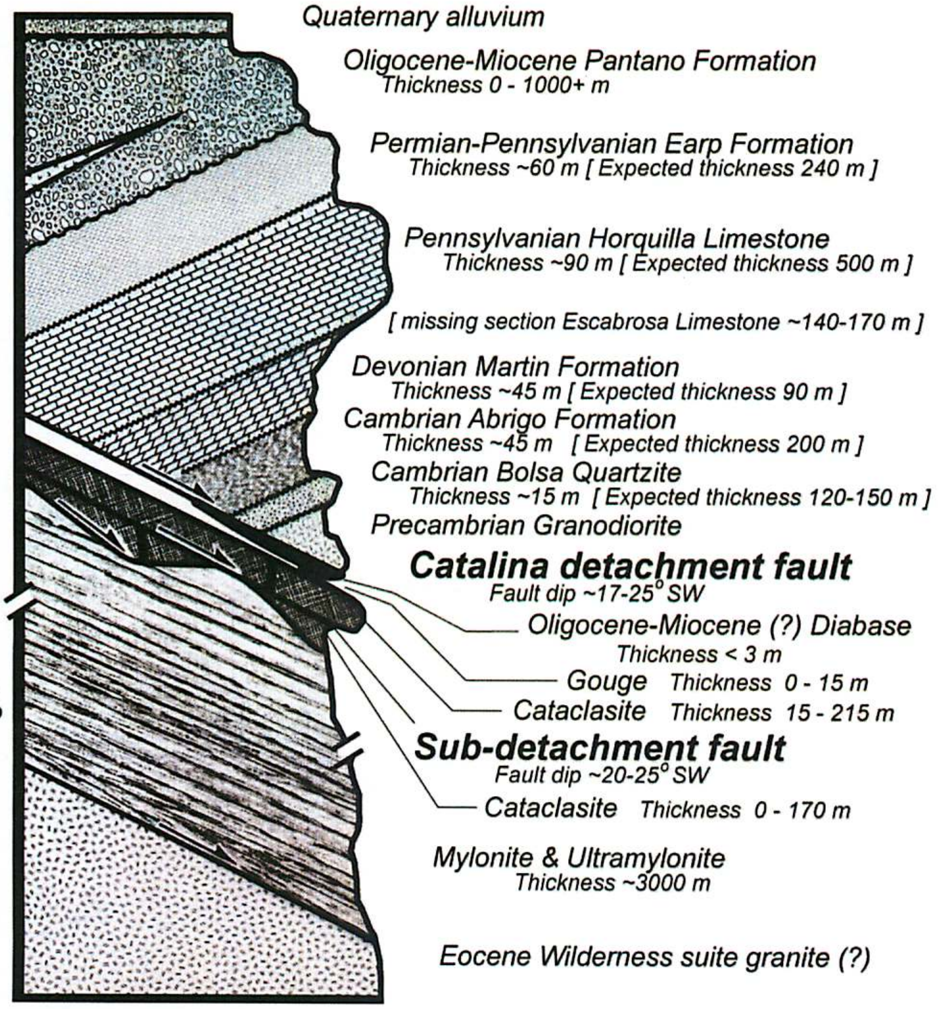

Figure 4: Profile of the Catalina Detachment Fault.

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Alluvial Fans

Christa Van Laerhoven

As a stream exits a canyon the bed width transitions from very narrow to very wide, causing the flow speed to decrease. All else being equal, a slower flow cannot suspend/move as much alluvium as a high speed flow. Thus, as the stream exits the canyon and its flow speed decreases the alluvium it was carrying is deposited, forming an alluvial fan.

Figure 1: an alluvial fan

Major features of alluvial fans:

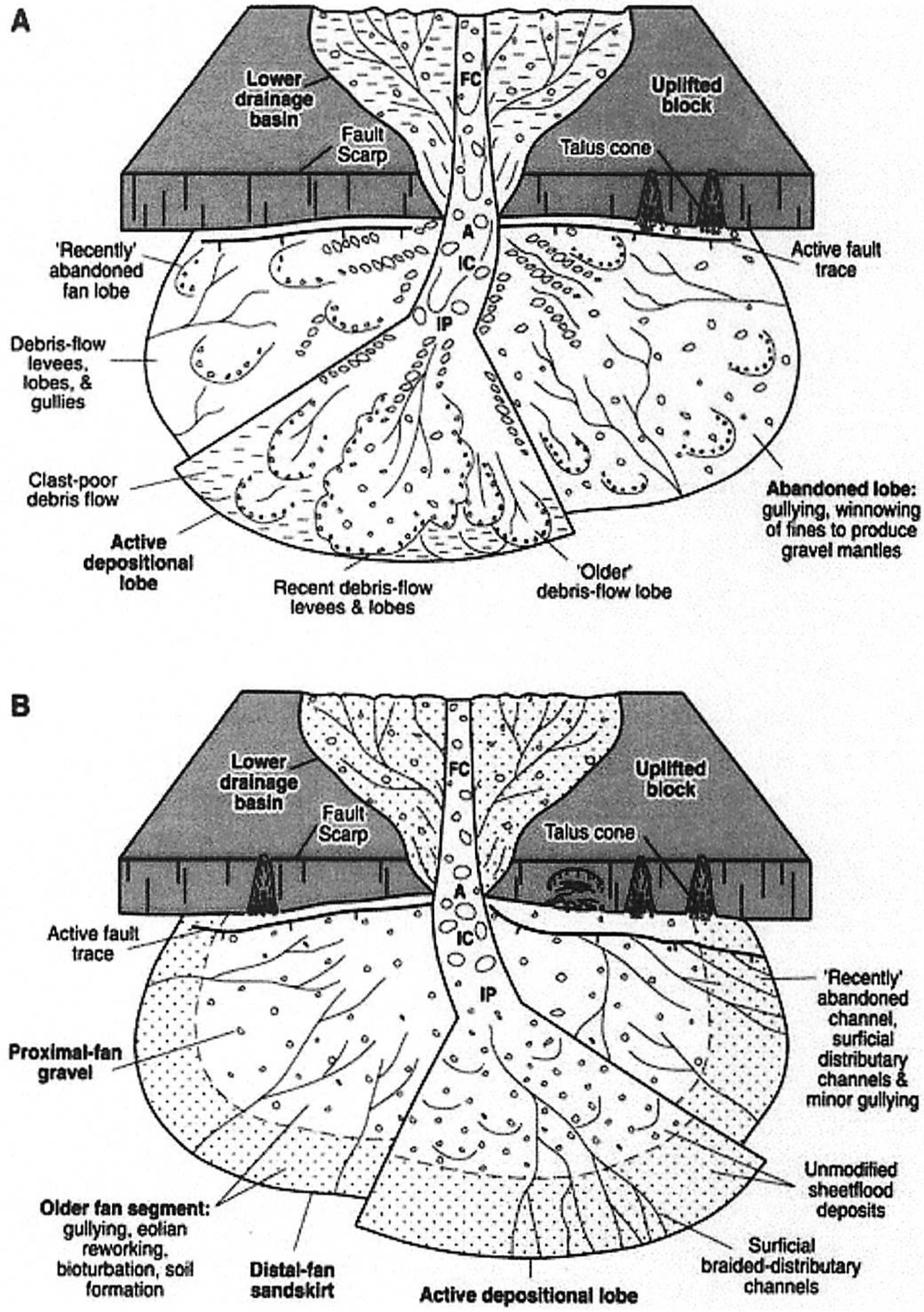
- **drainage basin**: the area from which the rain water is collected and where the sediment originates
- **feeder channel**: the main stream channel that feeds water and sediment to the fan
- **apex**: the highest point of the fan
- **incised channel**: the downslope continuation of the feeder channel that is cut into the fan (it may be one main channel or divide into several channels)
- **intersection point**: the intersection between the incised channel and the fan slope; where the incised channel ends and transitions to the fan slope
- **active depositional lobe**: the area of active sediment deposition
- **headward-eroding gullies**: gullies on the fan that erode towards the head/apex of the fan; if these gullies erode enough to intersect with the incised channel this can change the active depositional lobe

Sorting: the alluvium making up the fan is not well sorted but there is a general trend towards finer grains with increasing radial distance from the fan apex. "Wet" alluvial fans are better sorted than "dry" (debris flow dominated) ones.

Figure 2: (from Blair and McPherson 2009)

A. Alluvial fan dominated by water flows;
B. Alluvial fan dominated by debris flows.

Notation:
FC: drainage basin feeder channel;
A: fan apex;
IC: incised channel;
IP: fan intersection point



Ideal conditions for alluvial fans:

- topography such that a previously well confined stream will suddenly lose that confinement
- copious sediment production in the drainage basin
- a lack of erosional processes that would transport the alluvial fan sediment away

Processes:

Individual depositional events tend to form deposits that are narrower than they are wide. It is the combination of many of these events (as the direction of the incised channel changes) that form the fan as a whole.

The character of the depositional processes depends on:

- characteristics of the basin into which the alluvium is being deposited
- amount of rainfall into the drainage region
- character of rainfall (steady vs sporadic)

The flows that deposit sediment on to an alluvial fan can have a wide range of viscosities: normal water flows to mud flows.

The location of the active depositional area will change with the direction of the incised channel. The incised channel can change direction by being breached by one of the headward-eroding gullies or by infill of the channel.

Planetary connection:

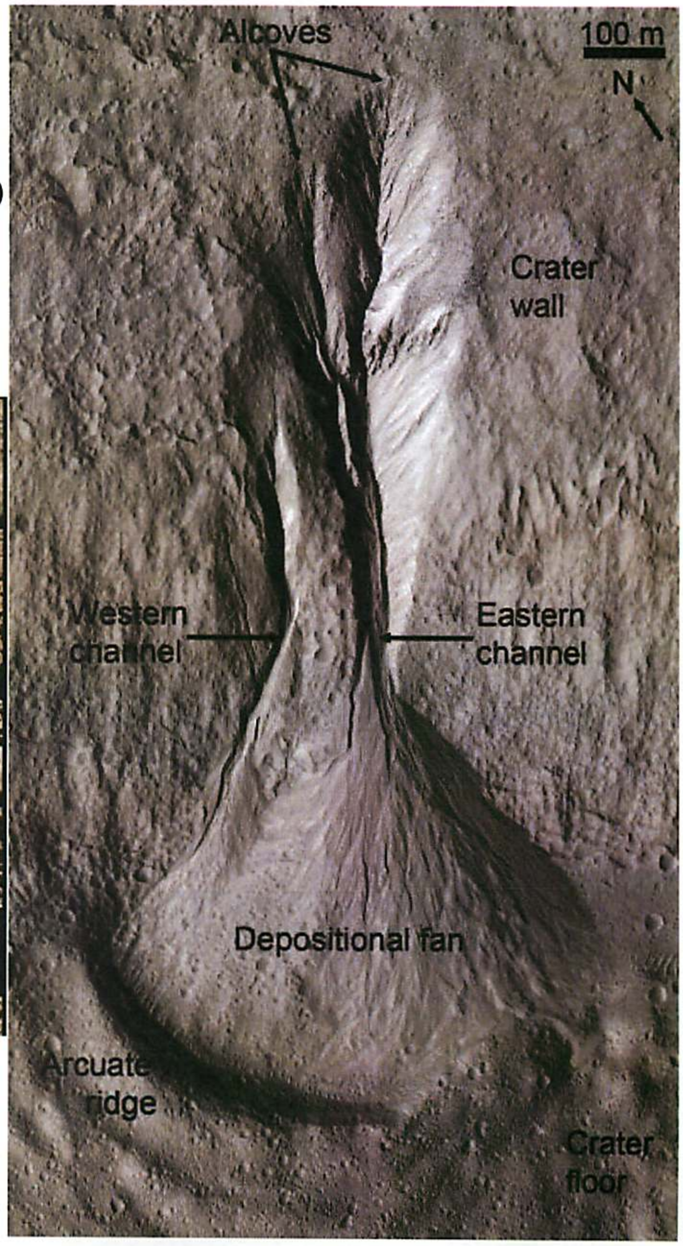


Figure 4 (right): Possible alluvial fans have been found on Mars (credit: NASA/JPL/UofA)

Figure 5 (below): Curiosity has discovered deposits that appear to have been emplaced by fluvial processes (credit: NASA/JPL)

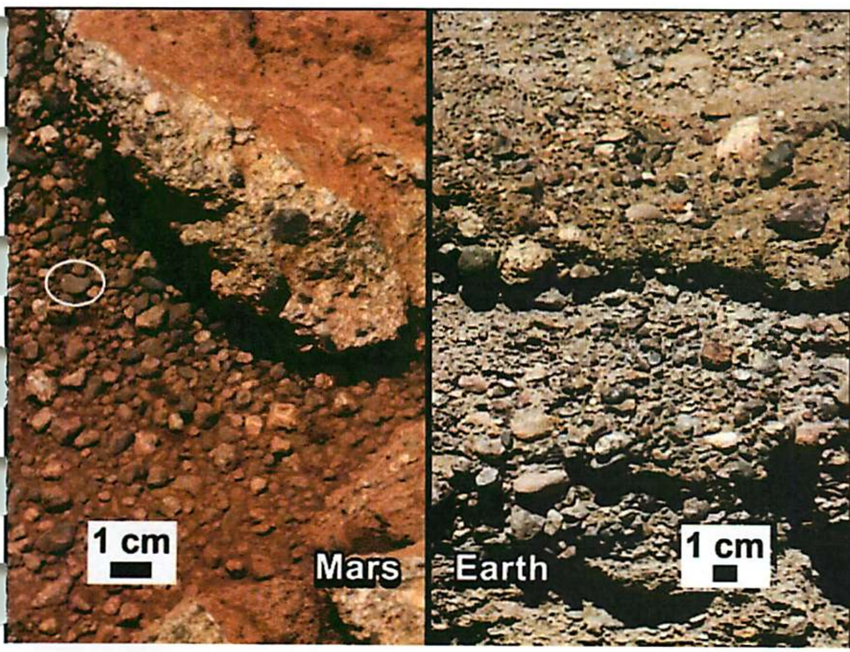
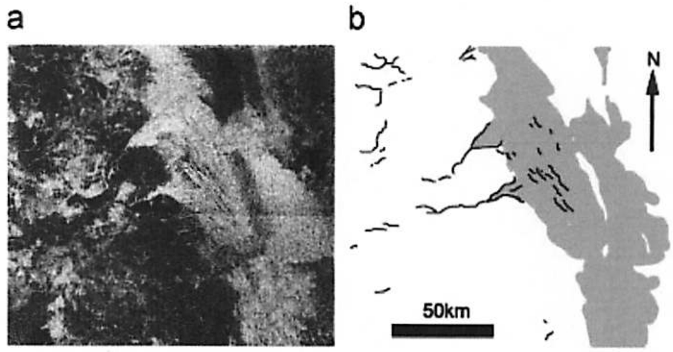


Figure 6: Possible alluvial fans on Titan (Lorenz et al. 2008)



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Tucson-Area Groundwater

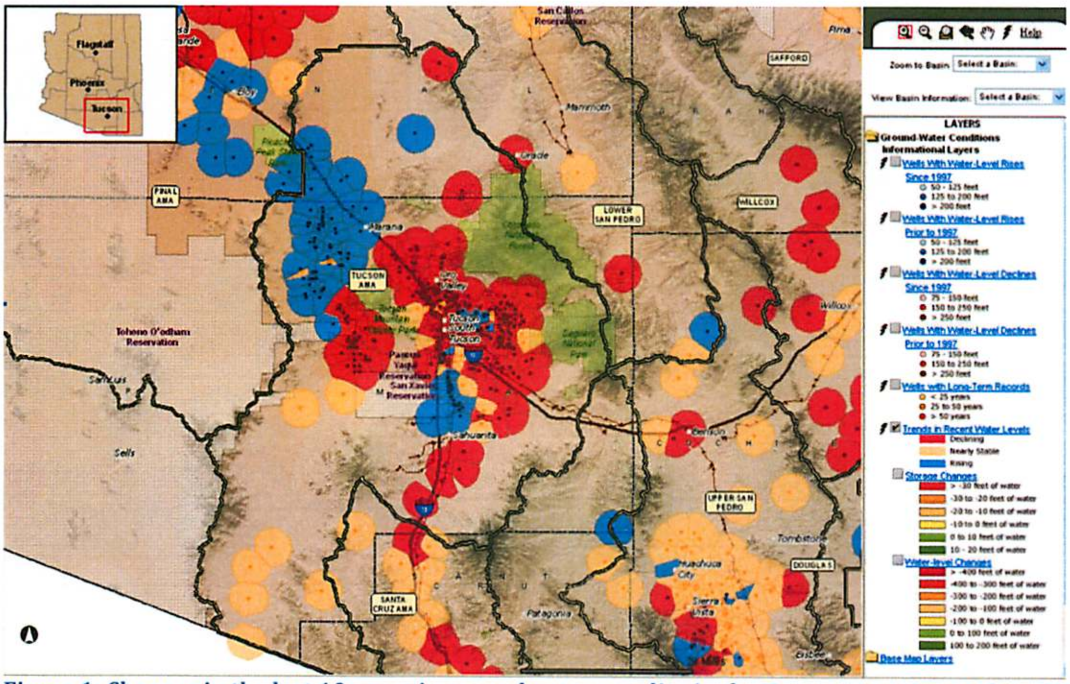


Figure 1: Changes in the last 10 years in groundwater supplies in the Tucson area; image from USGS ~2008

The Willcox Basin

- hydrologically isolated area
- ~4950 km^2
- alluvial deposits are main source of groundwater
    - interbedding of coarse stream bed and fine-grained lake bed material creates artesian conditions in some areas and perched groundwater in others
- general direction of flow is towards agricultural centers and playa
- recharge estimated at ~10^4 acre-feet/year
- usage estimated at ~10^5 acre-feet/year
    - irrigation for pistachio and pecan orchards
- formation of earth fissures


Figure 2: Topography of the Willcox Basin, with the location of Willcox Playa highlighted; image from Google Maps

Earth Fissures

Causes:

- pumping removes groundwater from pore space in sediments
- loss of support results in compaction
- surface fissures form where differential compaction occurs

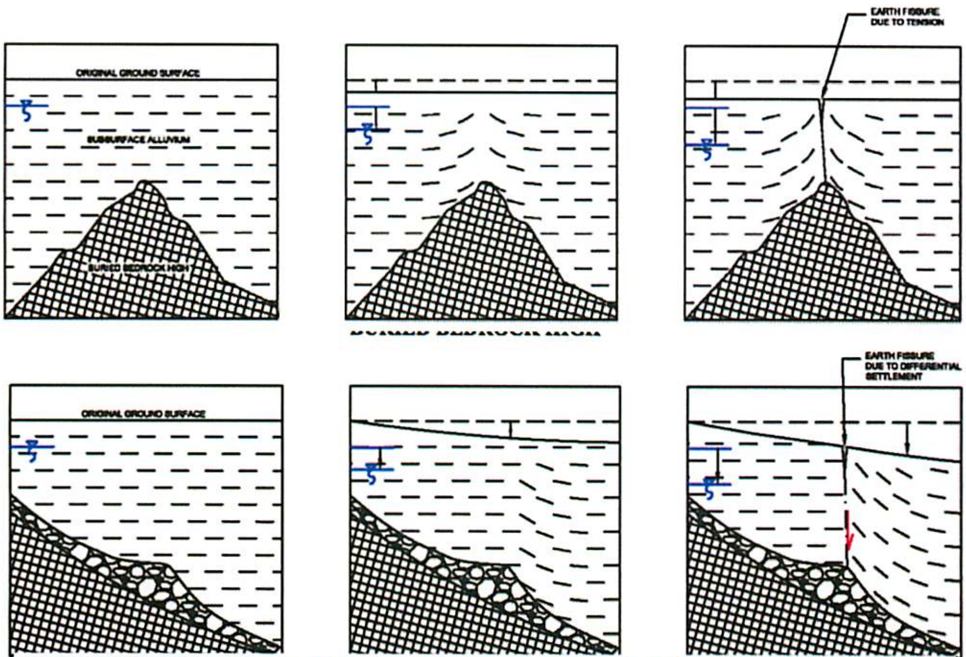


Figure 3: Possible sources of fissure-causing tension; image from Neely 2011

Propagation:

- hairline cracks form on surface across drainage areas
- surface water can seep in and weaken subsurface structure
  - can lead to abrupt appearance of fissures

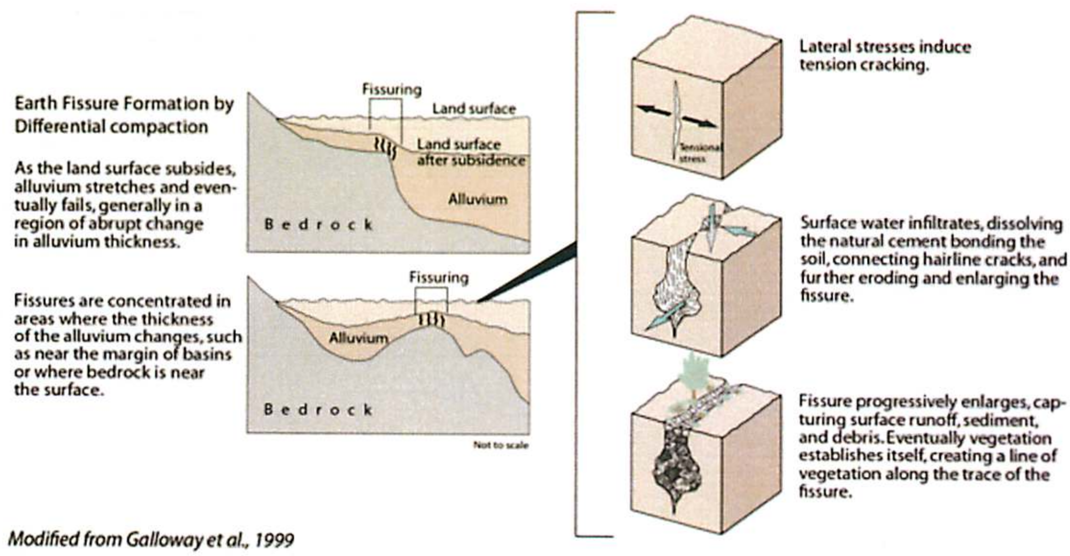


Figure 4: Formation and propagation of fissures is caused by differential compaction of subsurface features; image from Cook 2011

Detection and Identification

- track subsidence with Interferometric Synthetic Aperture Radar (InSAR)
- good correlation found with appearance of fissures
- some areas show subsidence but no fissures
- best repair mechanism is replenishing groundwater

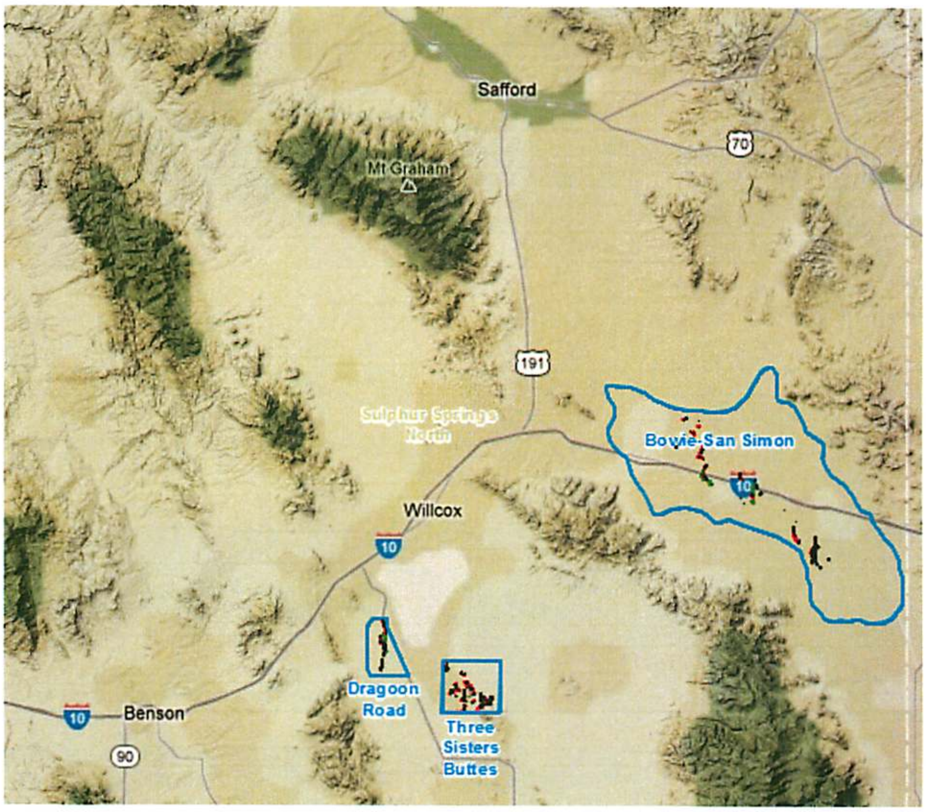


Figure 5: Location of earth fissures near the Willcox Playa; image from AZGS

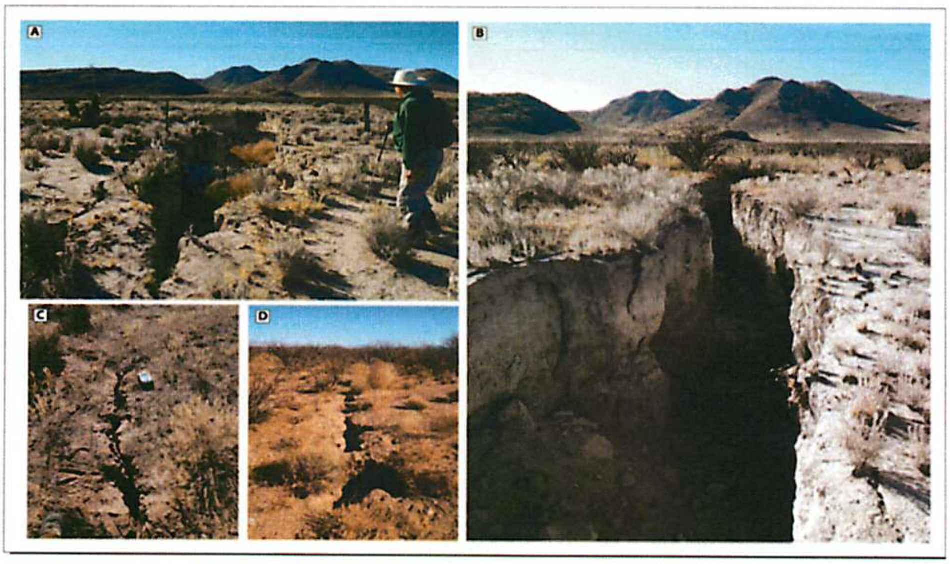


Figure 6: Surface features in Cochise County; A and B show fissures that have recently opened, while C and D show cracks and potholes that indicate where fissures may open in the future; image from Cook 2011

Giant Dessication Cracks

- common near edges of Willcox Playa and edges of alluvial fans
- up to 100s of meters across, but shallow subsurface extension
- form in areas with fine-grained, clay-rich soil
- caused by prolonged drought or cycles of wetting and drying
    1) hairline cracks show
    2) piping and erosion below the surface
    3) manifestation of collapse features

Polygons on Mars

- range in size from meters to kilometers
- many proposed formation mechanisms
    - small polygons probably form from thermal contraction
    - large polygons (~6km average diameter)still under investigation
        - Hiesinger and Head (2000): tectonic uplift
        - Lane and Christensen (2000): Rayleigh convection below flood deposit
        - Cooke et al. (2011) and Moscardelli et al. (2012)
    - Cooke and Moscardelli model
        - analogous to deep-water polygons on Earth
            - ~1 km in diameter
            - sediments with high porosity and low permeability
            - particle size more important than composition
        - possibly subaqueous process
        - compaction of fine-grained wet sediment
        - and/or water removal by increase in salinity
        - fault lines may indicate tops of subsurface features

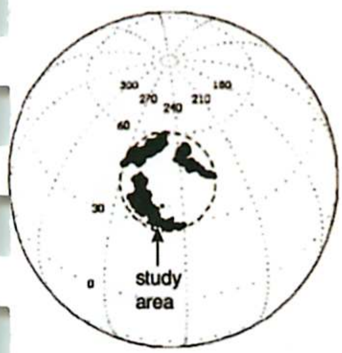
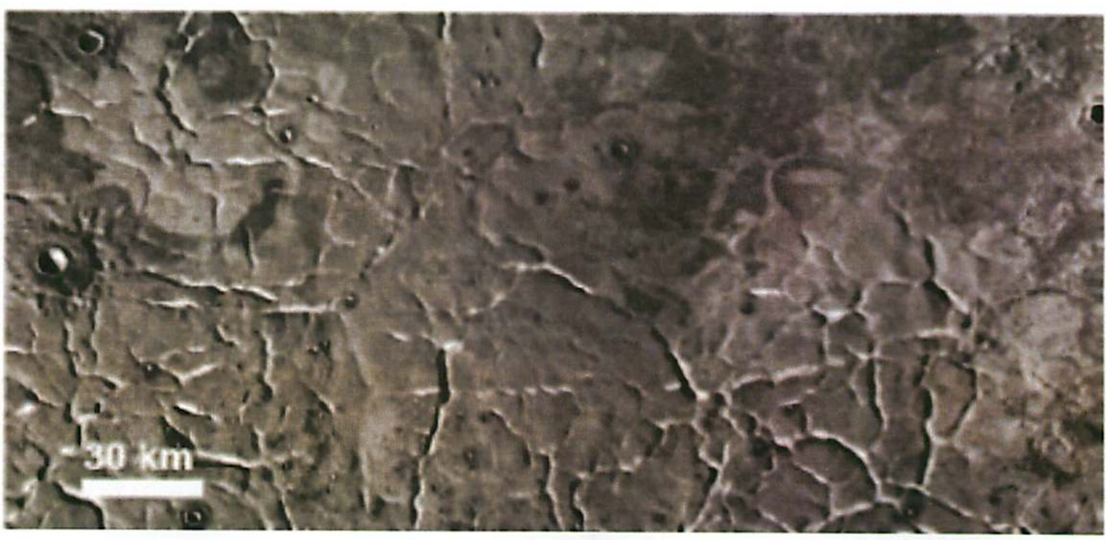


Figure 7: A. Area of study and B. THEMIS infrared image of typical polygons in Utopia Planitia, Mars; image from Cooke et al. 2011

B



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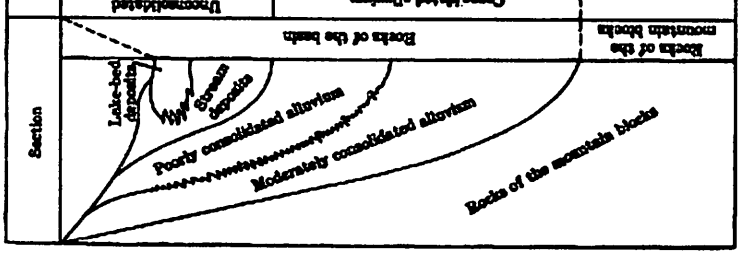
BLE 2.—*Columnar section, stratigraphic table, and water-bearing characteristics of rock units in the Willcox basin*

Section:



	Geologic unit	Description	Water-bearing characteristics
Rocks of the basin — Unconsolidated alluvium	Lake-bed deposits	Black to gray clay and silt, locally overlain by thin beach gravel and sand dunes	Fine-grained materials have very low permeability and are not considered to be water bearing; may act as an important local confining layer in areas near the Willcox Playa
Rocks of the basin — Unconsolidated alluvium	Stream deposits	Pale-red to light-brown lenticular interbedded gravel, sand, silt, and clay	Sand and gravel beds in this unit are highly permeable and yield large quantities of water to irrigation and domestic wells; probably the most productive aquifer in the basin
	—UNCONFORMITY—		
Rocks of the basin — Consolidated alluvium	Poorly consolidated alluvium	Poorly indurated lenticular light-reddish-gray beds of sand, gravel, silt, and clay	Unit generally has low to moderate permeability; yields moderate to relatively large quantities of water to wells in the Kansas Settlement area if sufficient thickness is penetrated
Rocks of the basin — Consolidated alluvium	Moderately consolidated alluvium	Moderately indurated stream-deposited beds of gray conglomerate, sandstone, and mudstone; materials composed of angular to rounded rhyolitic and andesitic volcanic fragments in a matrix of sand and fine-grained material derived from surrounding mountain areas; intercalated basaltic lava flows are deformed by tilting and normal faulting	Unit has very low to moderate permeability; produces small to moderate quantities of water sufficient for stock and domestic supplies
	—UNCONFORMITY—		
Rocks of the mountain blocks	Rocks of the mountain blocks	Igneous, metamorphic, and sedimentary units form the mountains and hills that ring the basin	Water-bearing characteristics are highly variable and depend on local geologic conditions; lithologic characteristics and high degree of structural deformation generally prohibit development of large water supplies from these rocks

St. David Formation

Melissa Dykhuis

The **"Saint David Formation" (SDF)** is a group of sedimentary layers near St. David, AZ.

Composition

The SDF is composed of eroded material from the nearby mountain ranges:

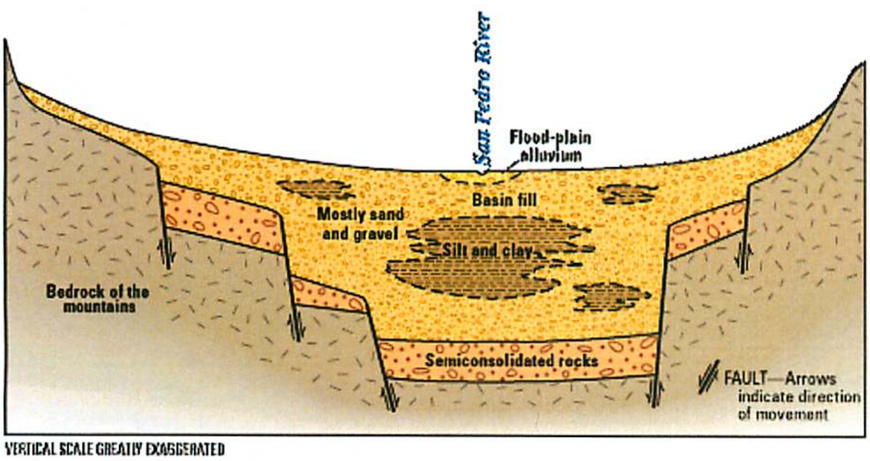
- → Precambrian (>550 Ma) plutonic and metamorphic rocks
- → Paleozoic (250-550 Ma) and Mesozoic (250-65 Ma) sedimentary rocks
- → Upper Cretaceous (100-65 Ma) volcanic and plutonic rocks

Layers

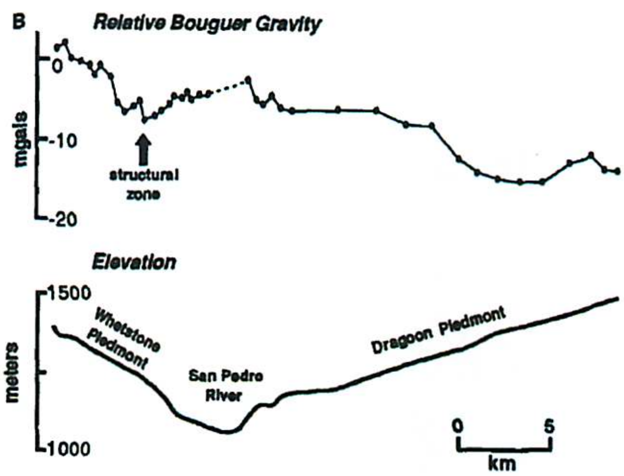
Lower: red mudstone and sandstone. Only 70m exposed, goes down another 100m.
Middle: red and green claystone, marl, tuff, tan sandstones. Sometimes conglomerate.
Upper: red sandy cobble conglomerate and pebbly sandstone, calcareous siltstone.

Tectonic "quiescence" during formation

→ Basin and range activity slowed down in late Miocene (5.5 Mya). We know this because sediment strata in some regions overlaps faults and are overlain on uplifted bedrock.
→ There's a "structural zone" to the west of the San Pedro, where the topography shows a monoclinical fold with a vertical displacement of up to 8m. This might be a reactivation of an underlying fault. But elsewhere, the topography is smooth compared to the gravity, suggesting that the basin was filled with sediment while tectonics wasn't shifting things around.



From the USGS 2006 Fact Sheet on hydrology in the region.



From Smith 1994.

Climate influences on the SDF

Smith 1994 argues that *climate changes*, rather than tectonic changes, were key during the formation of the SDF.

Formation history:

→ Lower layers were emplaced during dry conditions with monsoon rain in the summer (from elevated carbon and oxygen levels), circa 3.4 Ma.

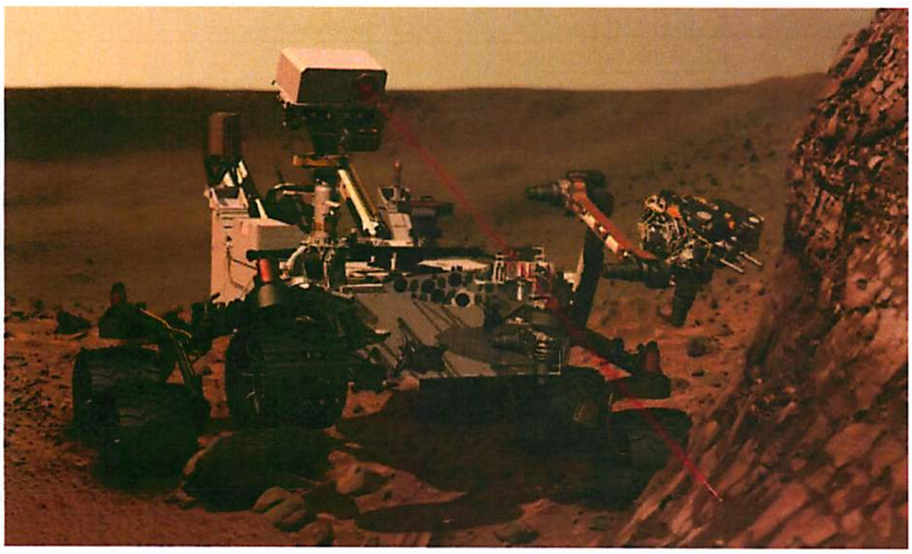
→ Middle layers were deposited under wetter conditions, with little seasonal variation, from 3.3-2.8 Ma (from plant "mosaicism", which show variations in $\delta^{13}C$ values but not $\delta^{18}O$).

→ Upper layers saw more seasonal variations again, monsoon-like climate, 2.8-2.5 Ma

A nearby example: Camp Verde, AZ (on the way to Flagstaff)

Remnant of an ancient lake, deposited from 10 to 2.5 Ma (longer timescale than SDF). Now evident as a sea of white limestone that was deposited last; underneath are alternating layers of white and red limestone that record transitions between higher and lower lake levels.

Planetary connection: Mars?



Most useful references:

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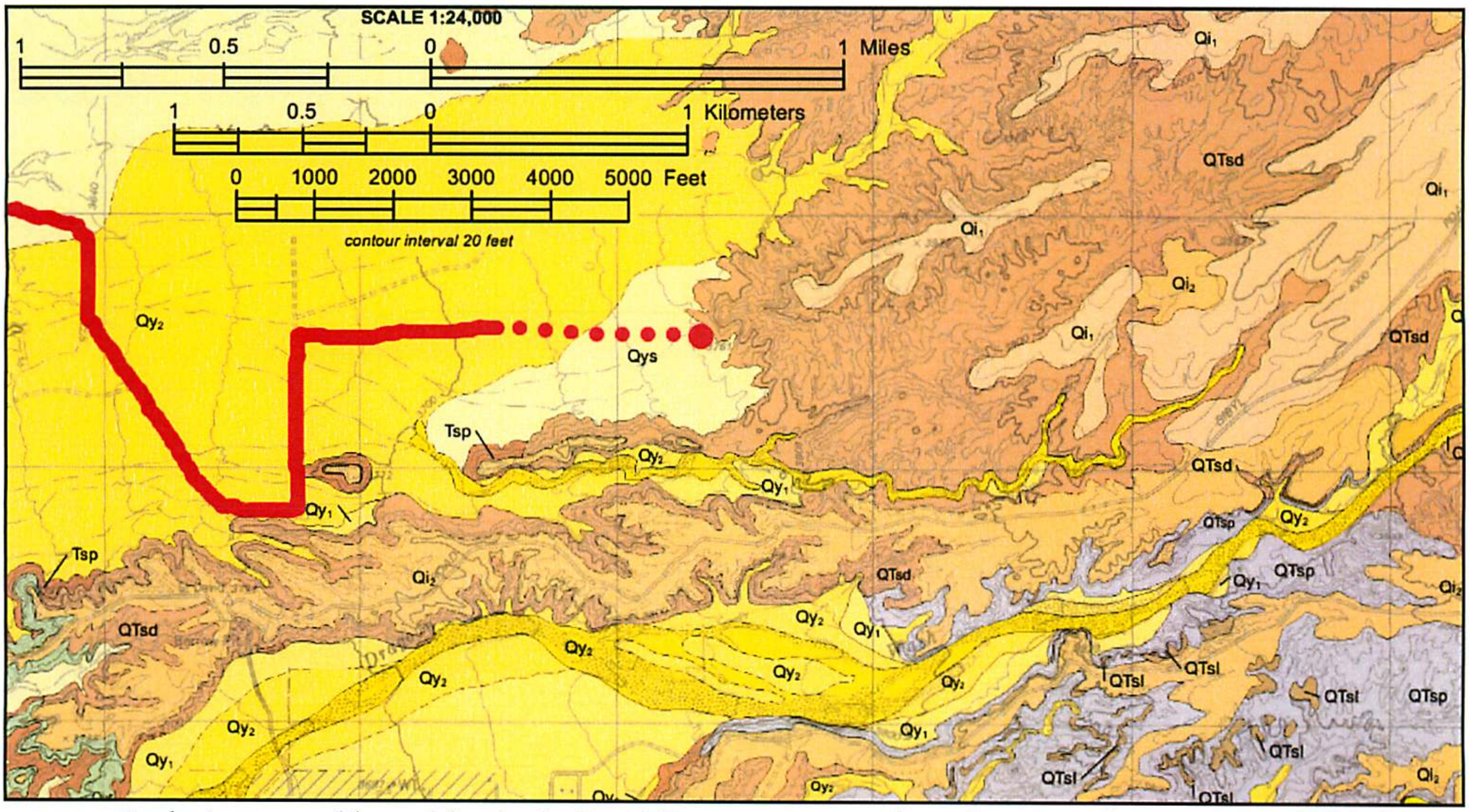
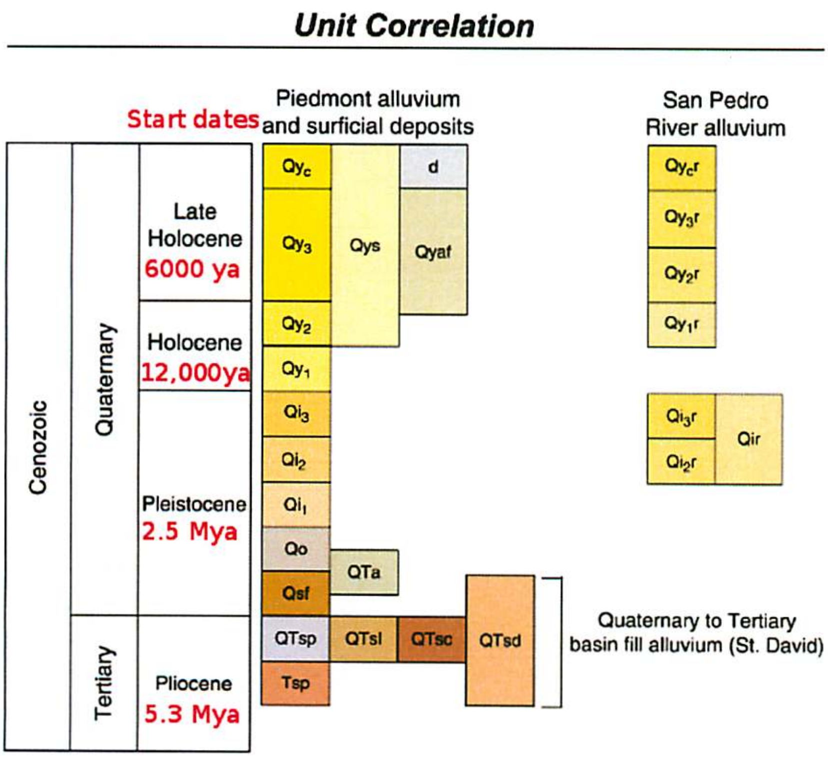
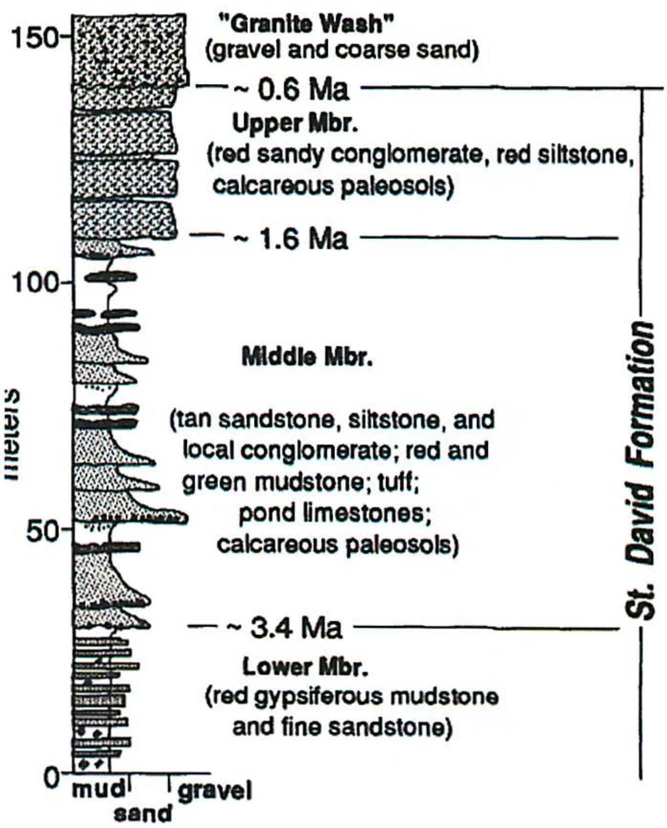


Geologic map and legend for the St. David Formation region, from the AZGS document repository.





Smith 1994

These are a lot of words that describe the geologic map. Feel free to read them if, like me, you think this stuff is cool.

Qys — **Fine-grained Holocene alluvium derived from the St. David Formation** - Thin to moderate (< 3m), fine-grained Holocene alluvium derived from, and overlying, basin fill deposits (units Qsf, QTsp, QTsd). It is composed mostly of silts and clays with color reflecting that of the parent material. Qys is typically found in fans at the base of basin fill outcrops along the edges of the peidmont.

Qy_2 — **Late Holocene alluvium** - Young deposits in low terraces and small channels that are part of the modern drainage system, and alluvial fan surfaces that were active prior to San Pedro River incision. Includes Qyc where not mapped separately. Along larger drainages, Qy2 sediment is generally poorly to very poorly-sorted sand, pebbles, cobbles, and boulders; terrace surfaces typically are mantled with pebbles, sand, and finer sediment. Qy2 alluvial fan deposits consist predominantly of moderately sorted sand and silt, with some pebbles and cobbles bar deposits. Channels on middle and upper piedmont areas generally are incised

Qy_1 — **Older Holocene alluvium** - Older Holocene terraces found at scattered locations along incised drainages throughout the study area, and isolated alluvial fans at the base of the piedmont. Qy1 surfaces are higher and less subject to inundation than adjacent Qy2 surfaces. In areas of deep incision these surfaces are now isolated from flooding. Qy1 terraces are generally planar but local surface relief may be up to 1 m where gravel bars are present. Qy1 surfaces are 2 to 6 m above adjacent active channels. Surfaces typically are sandy but locally have unvarnished open fine gravel lags or pebble and cobble deposits. Terraces along major drainages vary from 2 to 4 m thick Qy1 deposits over basin fill deposits to basin fill strath terraces with less than 1m of Qy1 deposits. Qy1 soils typically are weakly developed, with some soil structure but little clay and no to stage I calcium carbonate accumulation (see Machette, 1985, for description of stages of calcium carbonate accumulation in soils). Yellow brown (10YR Munsell soil color chart) soil color is similar to original fluvial deposits.

Qi_2 — **Middle to late Pleistocene alluvial fan and terrace deposits** - Moderately to highly dissected relict alluvial fans with strong soil development found throughout the map area. Qi2 surfaces are drained by well-developed, moderately to deeply incised tributary channel networks; channels are typically several meters below adjacent Qi2 surfaces. Well-preserved, planar Qi2 surfaces are smooth with scattered pebble and cobble lags; surface color is reddish brown; surface clasts are moderately to strongly varnished. More eroded, rounded Qi2 surfaces are characterized by strongly varnished, scattered, cobble to cobble and pebble lags with broad ridge-like topography. Soils typically contain reddened (5 to 7.5 YR), modestly clay-rich argillic horizons, with clay skins and subangular blocky structure. Underlying soil carbonate development is typically stage III with abundant carbonate through at least 1 m of the soil profile. This unit loosely correlates to Gray's (1965) granite wash unit.

Qi_1 — **Early to middle Pleistocene alluvial fan and terrace deposits** - Deeply dissected relict alluvial fans found on upper piedmonts. Qi1 surfaces form rounded ridges that are higher than adjacent Qi2 surfaces. Qi1 surfaces are drained well-developed, deeply incised (4 to 6 m) tributary channel networks. Underlying basin fill deposits are occasionally exposed along some ridge slopes and along wash banks. Well-preserved Qi1 surfaces have moderately to tightly packed cobble, boulder, and pebble lag. Surface clasts are strongly to very strongly varnished and often have thin carbonate rinds. More eroded, rounded Qi1 surfaces are characterized by course pebble, cobble and boulder lags with exposed carbonate horizons. Where well preserved, Qi1 soils are strongly developed with a dark red (5-2.5 YR), heavy clay argillic horizon, subangular blocky to prismatic structure, and stage III-IV carbonate accumulations.

QTsd — **Pliocene to early Pleistocene St. David Formation** - Unit QTsd is essentially equivalent to the Saint David Formation. The basin fill was mapped with this unit when (1) it was not possible to map individual facies at a scale of 1:24,000, (2) colluvium from overlying units obscured the basin fill, or (3) access was limited. The total thickness of QTsd deposits is not known. Unit QTs is composed of the following five basin fill units.

QTsp — **Pliocene-Pleistocene floodplain fan deposits** - Piedmont floodplain deposits composed mainly of paleosols, both vadose and hydromorphic paleosols. Includes interbedded tabular sands and gravels (QTsf), marls, pond limestones and interbedded red and green clays (QTsl), and channel conglomerates (QTsc) where not mapped separately. Roughly correlates to middle Saint David Formation. Interfingers with units Qsf in the upper sections.

Tsp — **Pliocene playa deposits (~3.4 to ~5 Ma)** - Unit Tsp is composed of red (5 to 10 YR) clay and silt with minor interbedded sand and occasional gypsum deposits. This unit correlates to the lower Saint David Formation and represent playa deposits of a closed basin.

Corrianne Lamkin

Fossils of the San Pedro Valley

"The San Pedro Valley is a prime area for studying life sequences because its fossil record preserves more than 6 million years of biotic changes....it has yielded the best record of early man and extinct mammals known on the continent" – Fossils of the San Pedro Valley

- **Short history of the San Pedro Valley**
  - The San Pedro Valley is a result of extensional southeast to northwest block faulting of the earth's crust
  - The Clovis hunters were the first people to enter the San Pedro Valley about 10,000 years ago.
    - Various sites around the San Pedro Valley show mammoth bones and the bones of other extinct mega-fauna are found in association with fire hearths, Clovis points, and tools.

Figure 1. Clovis points

- **Various Fossil Types found in the San Pedro Valley**
  - *Pliohippus*, the first truly single-hoofed horse, is thought to have evolved approximately seven million years ago in the Pliocene period.
    - These fossils have been located in the Arizona San Pedro Valley and are fairly common.

Figure 2. Pliohippus fossil

- Mammoth fossils
  - Murray Springs
    - Maimed mammoth, hunting camp, and 11 extinct bison

Figure 3. Mammoth remains

  - Lehner Mammoth-Kill Site
    - In 1955 a mammoth was excavated. When the bones were exposed, two Clovis projectile points were found among ribs of what was adjudged to be a young mammoth. A total of eight mammoths were determined to have been found.

Figure 4. Hunting Camping and Bison remains

Limestone Dissolution and Cave Formation

Ali Bramson

The dissolution of limestone occurs through the following reaction[1]:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + (HCO3)^{2-}$$

Carbon dioxide from the atmosphere can dissolve into water to form carbonic acid (H_2CO_3). This weakly acidic groundwater then reacts with the calcium carbonate in the rock to dissolve the rocks through a form of chemical erosion[2].

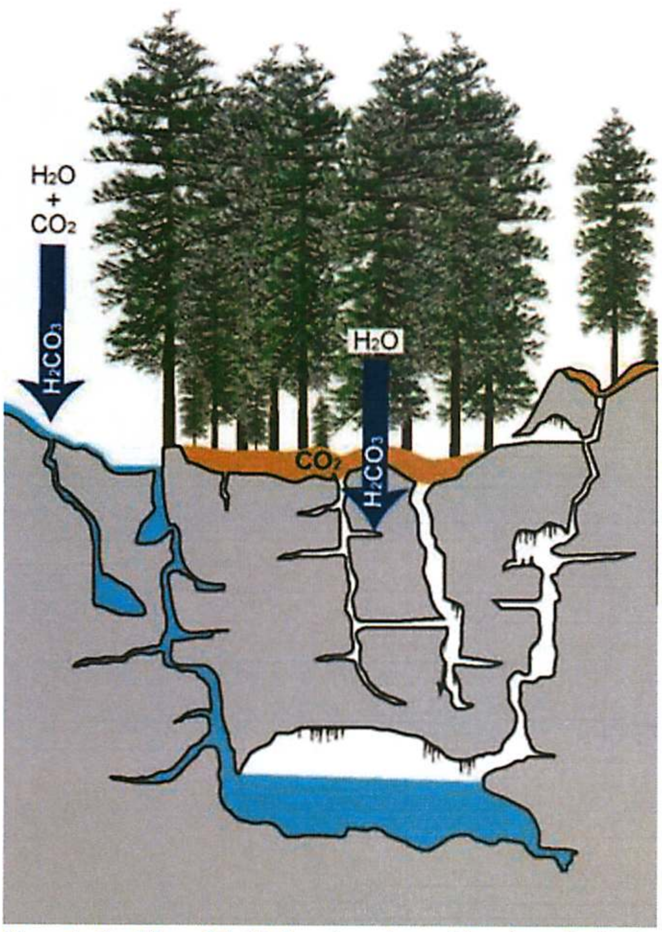


Figure 1: Fig. 1 from [7]: "Rainwater mixes with carbon dioxide in the atmosphere and soils to form carbonic acid (H_2CO_3), which acts to dissolve away limestone."

The rock type needed to form caves through this process is one which is >80% calcium carbonate, such as limestone or dolomite[2]. This rock must be fractured or jointed so that the water has a way of seeping into the rock and reacting with it. On Earth, vegetation can help add more acid into the system, amplifying the karst reaction[2] (see Figure 1).

Limestone rocks being dissolved by rainwater through this process leads to the karst terrain seen on Earth and can be recognized by the formation of pits, hollows and underground caves[1]. It is a simple reaction but is very dependent on concentration and temperature of the water.

Limestone dissolution occurs is a slow process, and most caves formed through this mechanism require on the order of 100,000s of years to grow large enough for us to walk around in them[6].

As the reaction eats away at the $CaCO_3$, the fractures enlarge, creating tunnels that enlarge and eventually form the cave. The initial step of enlarging the fractures generally occurs right around the water table where there is a lot of movement of large amounts of water[5]. The more stable the water table is, the bigger the tunnels that can be due to the fact that the water will contact all surfaces of the tunnel and dissolution can happen on a larger scale[5]. A second stage of cave formation generally occurs when the water table lowers, moving the active cave formation to lower levels, and the already created cavities are stranded where air can enter, leading to $CaCO_3$ deposition features called speleothems.

After the cave has been formed, speleothems (cave formations of $CaCO_3$ such as stalagmites, columns and BACON... *yummm*) can appear. When a drop of water reaches the inside of the cave, it has dissolved limestone in it. When this water reacts with the air, Equation 1 is reversed, carbon dioxide escapes from the drop, and it leaves a residual amount of calcium carbonate.

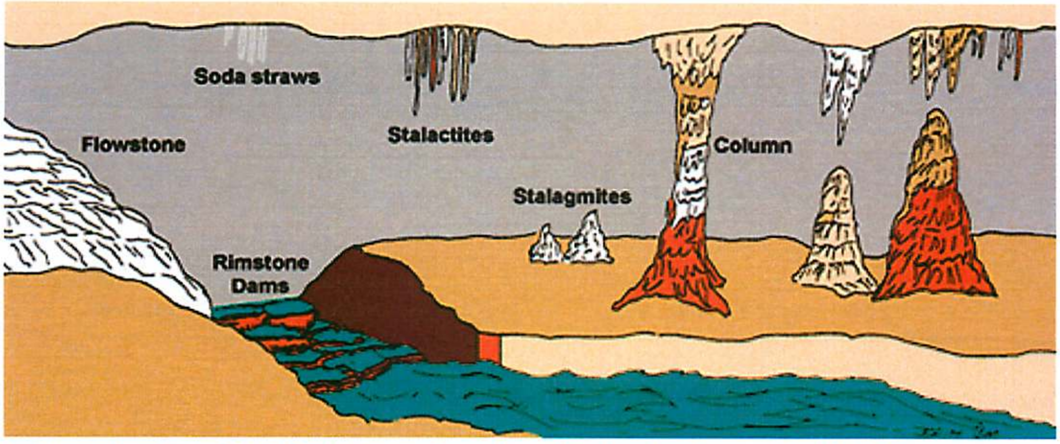


Figure 2: Some types of speleothems

http://mostateparks.com/sites/default/files/imagecache/unmodified/wysiwyg_imageupload/10/splthmcr.gif

For an example to understand the timescales on which speleothems form, stalactites (you know, those ones that need to hold on *tight*!) grow an average of ~1/2 inch per 100 years[2]. Stalagmites (they *might* reach the top!), form through the same process but from the ground up through droplets that have hit the ground and lost more CO_2, depositing more limestone.

Caves are awesome because they allow us to investigate subterranean processes. The fracture patterns seen in caves can tell us about past geologic activity, and the shape of the cave and features in it can show us how water flowed in the region. The regional aquifer can be observed, and since caves cut down through rock layers, they allow us to identify the stratigraphic layers of the area[7].

How this applies to Tucson area: Kartchner Caverns!

About 320 million years ago, Tucson was a shallow sea in which layers of sediment got deposited that turned into the Escabrosa limestone[3]. Then, 13-5 million years ago, Basin and Range tectonics led to the graben and horst topography with the Whetstone Mountains and San Pedro Valley, and this layer of Escabrosa limestone was faulted and downdropped[4]. Rainwater slowly seeped into the cracks and dissolved the limestone away into the Kartchner Caverns we have today.

Figure 3: Kartchner Caverns Big Room
http://azstateparks.com/Parks/KACA/KACA_images/KACA_G_03.jpg

Speculation for this on other planets:

Mars has a lot of caves but they are generally formed through volcanic lava tubes. However, all the evidence for underground water on Mars means that caves formed through mineral dissolution could be possible[8]. Limestone dissolution in particular is pretty unique to Earth considering limestone generally forms from biochemical processes. Carbonates have been seen in Martian meteorites[9] and were first detected on the large-scale on Mars from orbit in 2008[10]. Mars' atmosphere is mostly CO_2 so it would be likely that water on Mars could undergo the reaction to become a weak carbonic acid. This, combined with presence of carbonates or other minerals that can dissolve in weak acids, means that there is a chance there could be mineral dissolution-related cave formation on Mars, and karst-like topography has been found in HiRISE images. Figure 4 shows karst-like features (karren) on Mars from Figure 2 of Baioni et al [11].

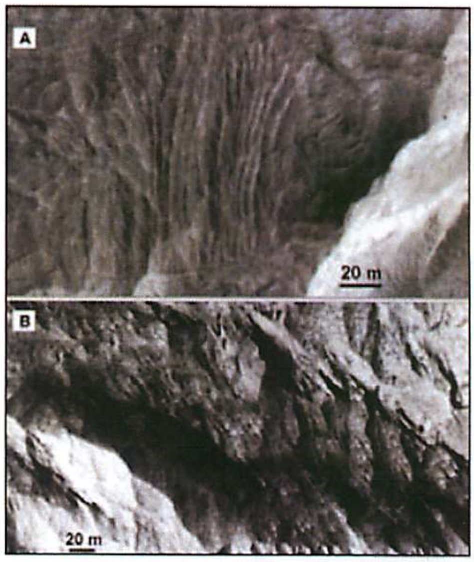


Fig. 2: Solutional surfaces. A: Linear karren developing along the slope in the western flank of ETD (MRO HiRISE image PSP_007153_1745; north upward). B: Solutional karren located in the north-eastern flank of ETD showing grapes-like shape (MRO HiRISE image PSP_004951_1745; north upward). Images were taken by HIRISE Web site (http://hirise.lpl.arizona.edu).

Figure 4: Karst-like features on Mars, figure from Baioni et al 2009.

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Local history – post ice-age to Spanish missions

Binna Kim

Figure 1 Anasazi Petroglyphs

Arizona is one of the oldest inhabited places in the United States around 12000 years ago. First inhabitants are the Anasazi, or also called Ancestral Puebloans, the Hohokam and the Mogollon. The Anasazi lived in the northwestern Arizona. They are known as building multi-room houses in caves. They also built circular buildings for ceremonies. The Hohokam lived in the central part of Arizona. They are known as farmers and they developed irrigation canal systems around 500AD. There are evidence of agricultural settlements, irrigation canals and farming such as corn, beans, and other crops along the river. The Casa Grande ruins are from the Hohokam. The Mogollon lived in the eastern Arizona and western New Mexico. The Anasazi and the Hohokam flourished their civilization most between 1100 and 1300 AD. However, the Anasazi, Hohokam and the Mogollon disappeared mysteriously around 1400AD possibly due to reduced food supplies from dried farmland. At this time Spanish explorers arrived as well as Navajo, Hopi, Apache and other tribes. Athabaskan-speaking people migrated to the Arizona-New Mexico region between 1300 and 1500 AD and some were classified as Navajo and Apache. The Hopi are known as most likely direct descendents of the Anasazi. And they are known for their ceremonial cycles that are still performed in their villages today. Navajo were known as a migrated group from Alaska and Canada and began arriving in the Southwest between 1000 and 1200 A.D. Part of this group settled and adopted the agricultural lifestyle of the Hopi and Pueblo peoples. The Apache lived in the eastern and central part of Arizona. The Apache are known for their ceremonies, particularly for girls. So, one woman is chosen to act as a "godmother" to guide and to care for girls becoming women. In the 1600s, Franciscan missionaries arrived as well as traders and trappers in the early 19th century.

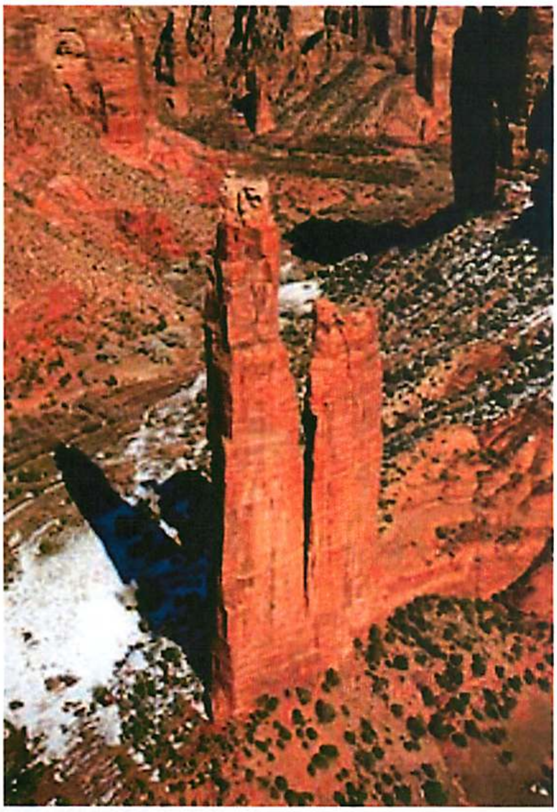

Figure 2 Spider rock

Figure 3 Casa Grande, Az - Hohokam Settlement

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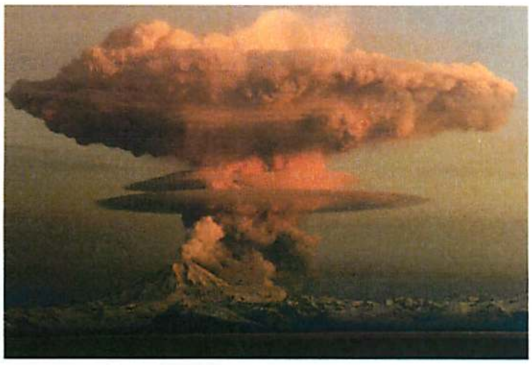
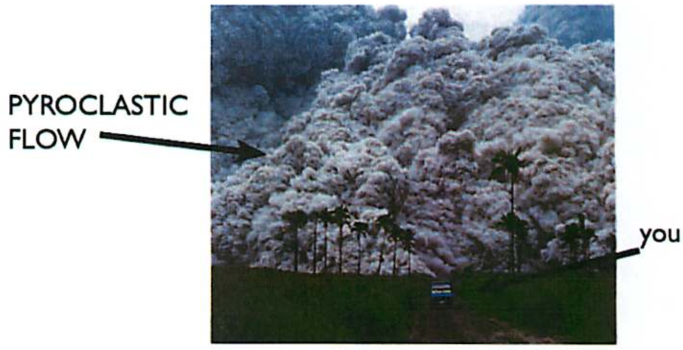
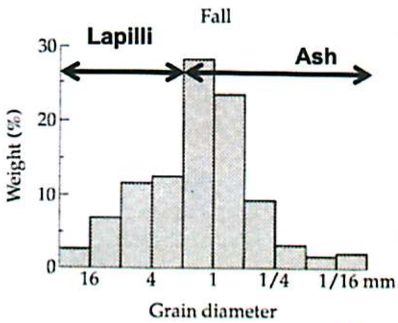
PYROCLASTIC VOLCANISM, TUFF FORMATION AND YOU

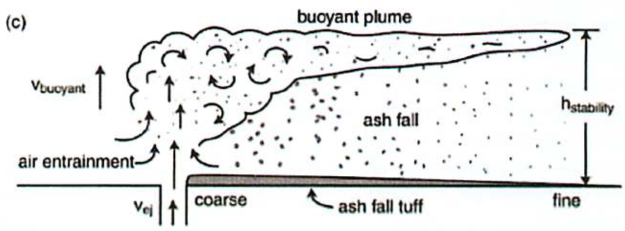
Davin Flateau



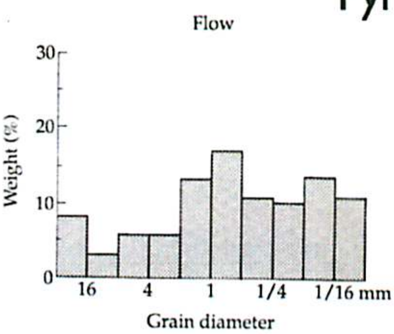


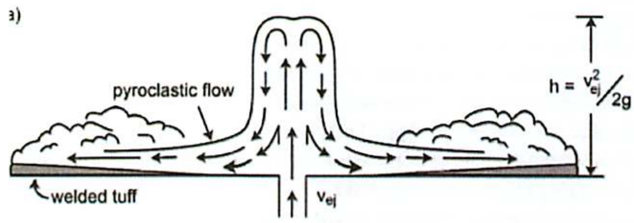
Pyroclastic Fall



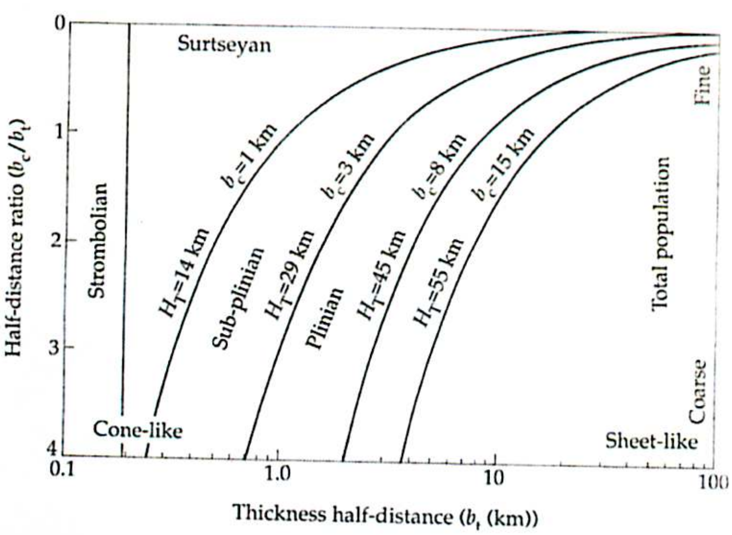


Pyroclastic Flow





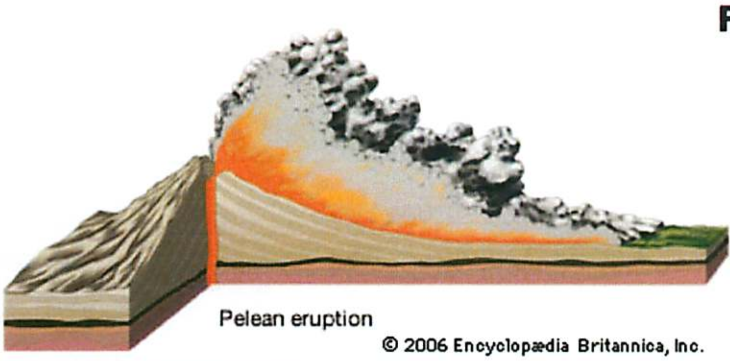
Pyroclastic Falls



Pyroclastic Falls

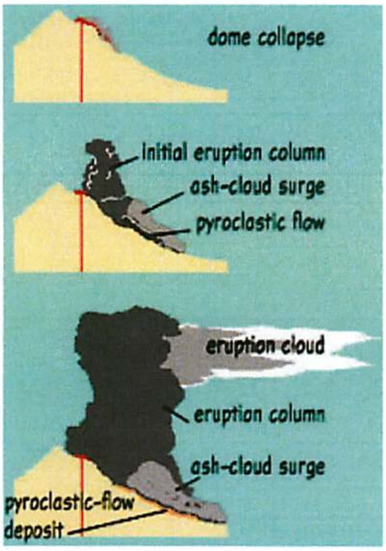
- Can be categorized from ancient deposits:
  - Distance which deposits halves in thickness (b_t)
  - Distance over which maximum clast halves in size (b_c)
  - Usually well sorted
  - Evenly coats pre-existing topography

Pyroclastic Flows

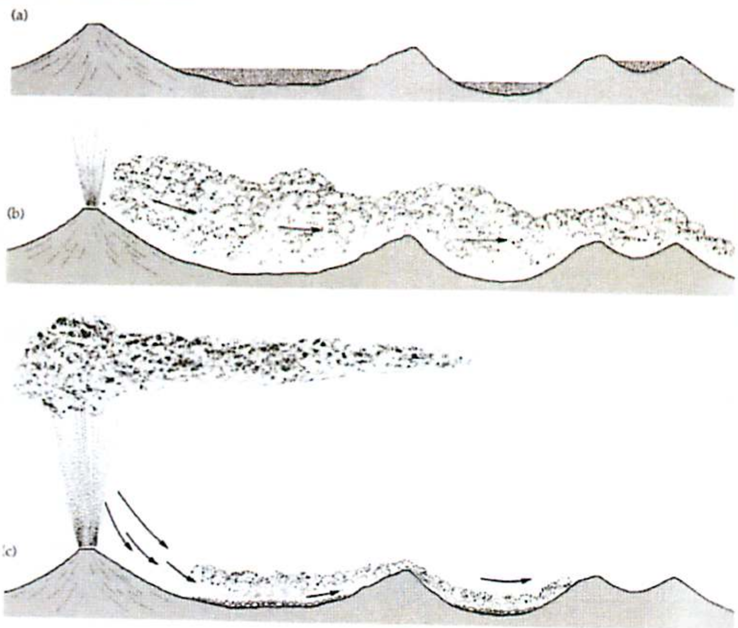


Pyroclastic Flows

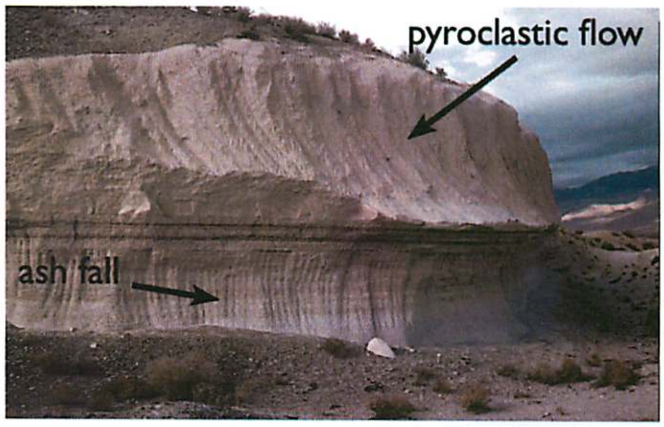
- Fluidized mix of hot gases and clasts
- High velocity (upward of 700 km/h)
- ~1000C
- Usually not well sorted
- Fills hollows in pre-existing topography
- Produces welded tuff



Tuff Formation



Bishop Tuff



Caldera collapse and megabreccia in the Tucson Mountains

Catherine Elder

1 Megabreccia or "Tucson Mountain Chaos"

- "Tucson Mountain Chaos" is made of Paleozoic sedimentary rocks, Jurassic silicic volcanic rocks, and Cretaceous sedimentary and volcanic rocks in a matrix of sandstone or tuff (Lipman 1994, Chronic 1983)..... so it looks confusing. Fragments range in size from a few centimeters to 0.5 km in diameter (Lipman 1976, 1994).
- "Tucson Mountain Chaos" has been interpreted as the sole of an imbricate thrust sheet, sedimentary talus deposits that accumulated adjacent to a tectonic scarp, pyroclastic flow breccias, and the result of fluidized emplacement by intrusive magma (Lipman 1976 references therein).
- "Roadside Geology of Arizona" from 2003 (Chronic 1983) still says that the exact origin of the "Tucson Mountain Chaos" is unknown.
- Here is the explanation that is now more (Lipman 1994) or less (Shakel 2009) accepted:

  As the caldera collapsed, pre-caldera material slumped into the caldera where Cat Mountain Tuff had ponded forming the megabreccia we see today (Lucchitta 2001, Lipman 1994). Some of the avalanching material landed in the tuff as the tuff was forming resulting in tuff interlayered with megabreccia (Lucchitta 2001).
- Megabreccias are only observed in eroded calderas, because it is a deeper structural zone usually found under mesobreccia which contains smaller fragments (Lipman 1976). They have also been observed at other calderas including those in the San Juan Mountains in Colorado, Bennett Lake cauldron complex in British Colombia Grizzly Peak caldera in the Sawatch Range of central Colorado (Lipman 1976).

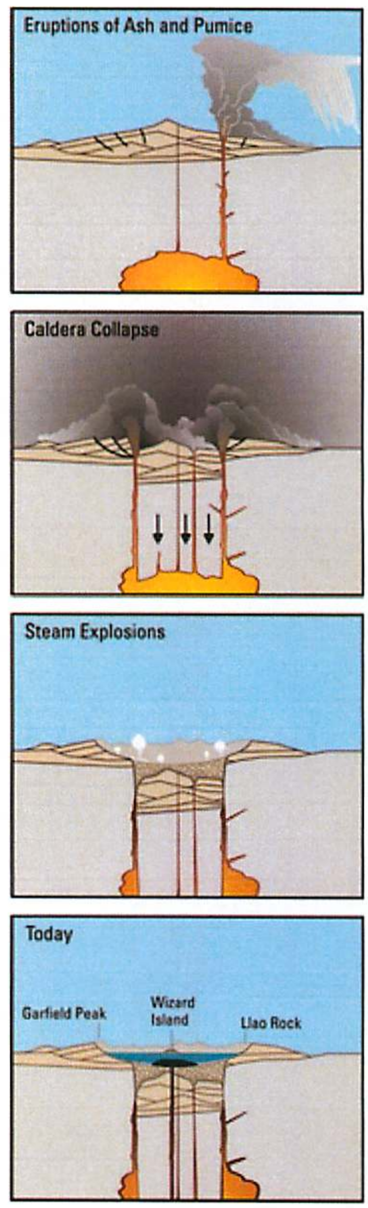


Figure 1: Example formation of a caldera (Mount Mazama pictured here) from wikipedia's Caldera article.

2 Types of rock in the area

- **Pre-caldera** including ash-flow tuff from an older caldera, sandstone, and shale (Lucchitta 2001).
- **Rocks within the caldera** including two interbedded units:
  - *ash-flow tuff* - once flowed away from this caldera (Lucchitta 2001). Now known as "Cat Mountain Tuff," but formerly called "Cat Mountain Rhyolite" (Lipman 1994).
  - *Megabreccia* - large angular blocks of pre-caldera rocks jumbled together by the collapse of the walls into the caldera (Lucchitta 2001).
- **Post-caldera igneous rocks** which formed during a renewal of igneous activity. Most are plutons that intruded and metamorphosed the caldera and pre-caldera rocks (Lucchitta 2001).

3 Tilting the caldera

- Virtually the entire mountain range is an oblique section through the interior of a caldera. The caldera margins are now covered by basin fill (Lipman 1994).
- The inferred dimensions of the caldera are about 2025 km which is typical of late Cenozoic calderas in the Western US (Lipman 1994).

4 Planetary Connection

- There are calderas on Mars, Venus, and Io.
- It would be hard to identify something like the Tucson Mountains as an eroded caldera remotely.
- Deeply eroded calderas on Earth provide insight into the formation of calderas in general.
- Breccia - impact vs caldera?

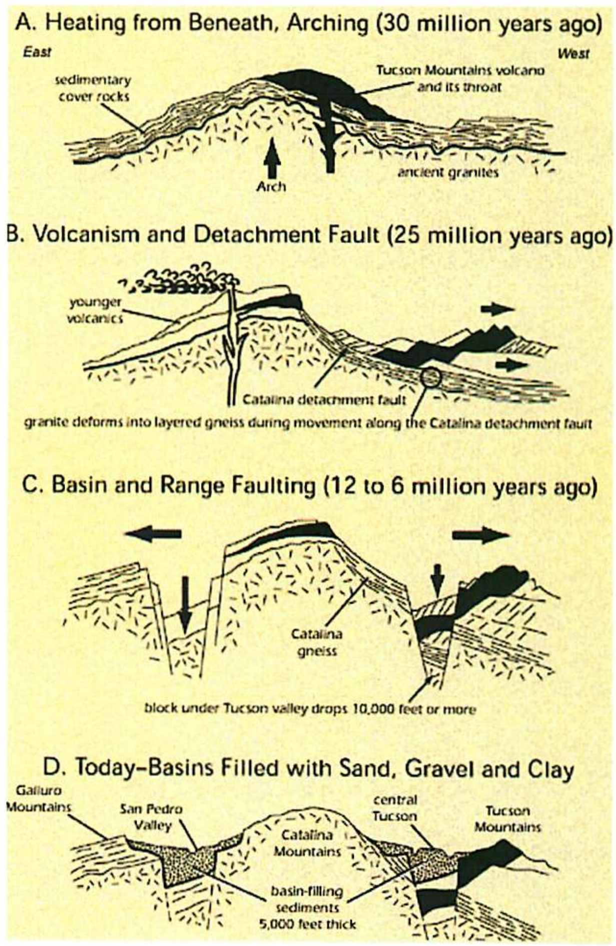


Figure 2: Cartoon illustrating the formation of the Catalina and Tucson Mountains from http://www.desertmuseum.org/books/nhsd_geologic_origin.php#76

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Hydrothermal Mineralization and Ore Formation

The process of *mineralization* occurs in rock systems and results in the formation of high concentrations of economically important compounds (typically metals); this region of material is called an *ore body*, and the physical rocks containing the metal are called the *ore.*

Mineralization is often the result of rock interacting with *hydrothermal fluids.* These fluids come from a variety of sources and carry with them dissolved metal species and rock constituents, which creates a pathway for the *precipitation* of valuable ore minerals within the host rock.

The specific mechanism for their generation uses the model of:

source ➔ *transport* ➔ *trap*

The 'source' refers to both the hydrothermal fluids, and the metal constituents that form the ore minerals. The fluids come from circulating sea water or meteoric water in the crust, and also magmatic water. The metals which become concentrated in the ore deposit often occur as trace elements within the host rocks that these hydrothermal fluids are interacting with. They are liberated from their host mineral phase during the interaction with hydrothermal fluids due to their relative incompatibility, the solubility of the mineral as a whole, or the decomposition of mineral structures at high temperatures.

The 'transport' refers to the movement of these species within the aqueous solution and their concentration in areas of eventual redeposition. The metals, once in solution, are transported usually as a *metal-bearing complex.* This requires a salt or similar soluble species to bind with the metal cation within the hydrothermal solution. These solutions often move through natural weaknesses in the rock, along joints/cracks/faults and through units with high porosity and permeability.

The 'trap' refers to the region of the system where this metal-carrying species becomes unstable and precipitates as an ore mineral. This can occur as a result of cooling temperatures or decreased pressures (generating these species unstable), further chemical reactions with the host rock material, changes in oxidation conditions, or degassing of the system (changing the 'carrying-capacity' of the aqueous system. These processes result in the deposition of these ore minerals in the host rock.

Hydrothermal ore deposits were recently reclassified using a scheme based on the type of hydrothermal fluid and the subsequent temperature and pressure ranges that govern the mineralization regimes. Each of these deposit types has a specific name and unique characteristics, with major types described in Table 1.

Table 1: Distinct hydrothermal ore deposits and their characteristics.

Deposit Type	Hydrothermal Fluid Type	Temperature (°C)	Pressure	Characteristics/ Major Mineralization
Porphyry Copper	magma/ meteoric	200-800	moderate	Porphyritic intrusive rocks and fluids that accompany the magma. As the magma cools to rock, envelopes of hydrothermal alteration enclose a core stockwork of mineralized material. Grade is typically <1%.
Epithermal	meteoric	50-300	low	Form at shallow depths, frequently as vein-like features with a variety of ore minerals and metals.
Mississippi Valley Type	meteoric	25-200	low	Carbonate-hosted lead-zinc deposits, named for their high concentration along the Mississippi River. Grade 4-14%.
Oceanic Ridge Deposits	sea water	20-300	low	Also known as volcanogenic massive sulfide (VMS) deposits. Layered deposits of sulfide minerals that form at hydrothermal vents on the sea floor. Large variety of ore minerals and metals.
SEDEX (Sediment ary Exhalative Deposits)	varied	low	low	Ore-bearing hydrothermal fluids are released into a large body of water and precipitate. Water may be meteoric or magma derived.

Each of these deposit types has been mined throughout the world as a source of metal-hosting minerals. Other types of deposits include those produced from heat generated in orogenic events and vein-like morphologies.

A simplified schematic for the formation of a hydrothermal ore body is outlined in Figure 1.

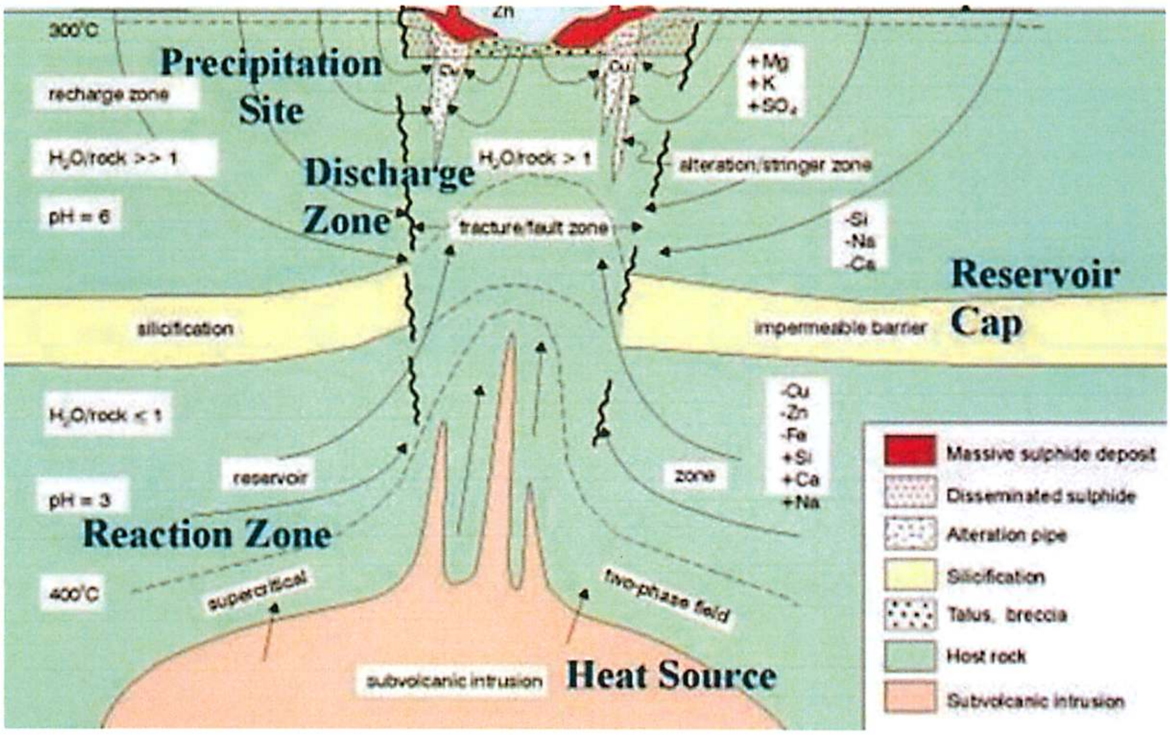

Figure 1: This image outlines the components critical for the development of a hydrothermal ore system. The heat source (in this case intrusive volcanics) reacts with a water source. This metal-bearing fluid travels through weakness planes in the rock to the precipitation site. There is often a reservoir cap (an impermeable layer) that prevents percolation of the fluids back towards the source region. Temperature and pH values are relative to the system. This schematic is meant to represent the volcanogenic massive sulfide (VMS) ore type.

Arizona Hydrothermal Ore Deposits:

The most prominent type of hydrothermal ore deposit found around Tucson and in Arizona in general is the porphyry copper deposit (Figure 2). Arizona produces up to 60% of the total copper in the United annually. Porphyry copper deposits often have accessory ore metals such as Au, Ag, or in the case of Arizona, Mo. The majority of these deposits are mined through open-pit processes in which rock is extracted from the ground and subjected to heavy acidic solutions to leach the material from its host mineral phase. Figure 3 shows the region south of Tucson and its numerous open pit mines. The ore bodies result from multiple intrusions of volcanic dikes with porphyritic textures and their associated magmatic and meteoric waters. These systems formed deep below the surface and have undergone erosion to expose them today.

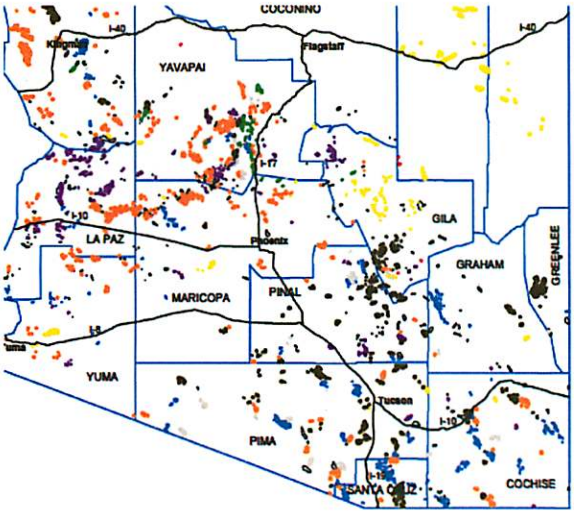

Figure 2: A map of Southern Arizona mineral deposits. Brown areas are porphyry copper, purple are copper veins, orange are gold, silver are silver, blue are Pb/Zn replacement, green are VMS and yellow/red are other iron/uranium ores.

Figure 3: An image showing the open pit mines in the region south of Tucson (north is in the direction to the left). Image was taken from the international space station. The image includes mines and tailings ponds.

Mineral Deposits in the Solar System:

Some scientists (and many more pseudo-scientists) have speculated on our ability to mine other planetary bodies for mineral resources. Popular targets include the metal and sulfides of asteroids, water and volatiles of comets, rare earth elements and helium from lunar soils, and possible volcanically produced minerals in the large igneous province-like regions on the surface of Mars. Recently, private companies (like planetaryresources.com) have been set-up to identify potential sources for mining on other planets, both for transport of material back to Earth, and for in-situ generation of fuel. The reality is, however, that we don't know enough about the geologic history of these other bodies to predict if and/or where any regions of high mineralization might be occurring.

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Mining in the Tucson Area

History and Current Controversy

Dyson Hale

Much of the ore in the Tucson area is in the form of porphyry copper deposits. Such deposits are common on the Pacific Rim and other subduction zones. Gold, silver, and molybdenum are also found in these deposits.

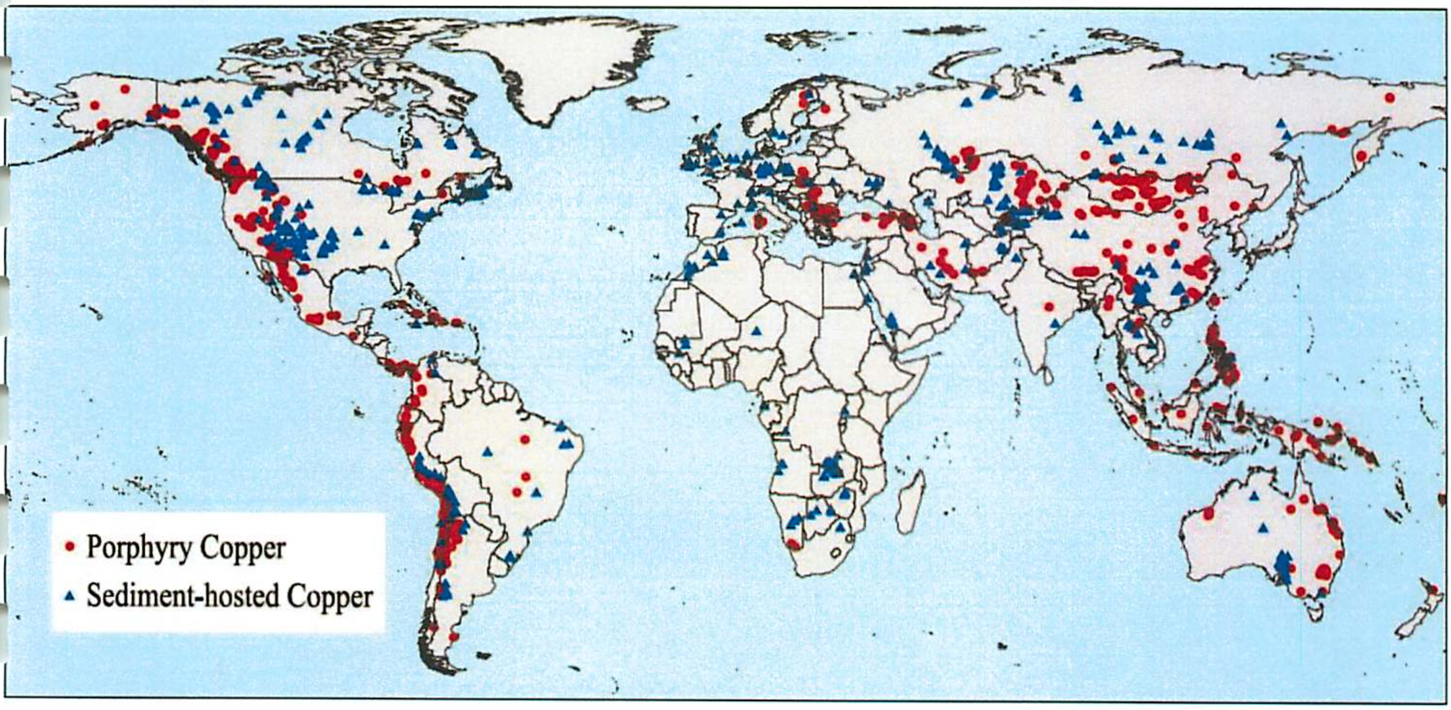


Figure 1: Copper deposits of the world (from Facts About Copper, geology.com)

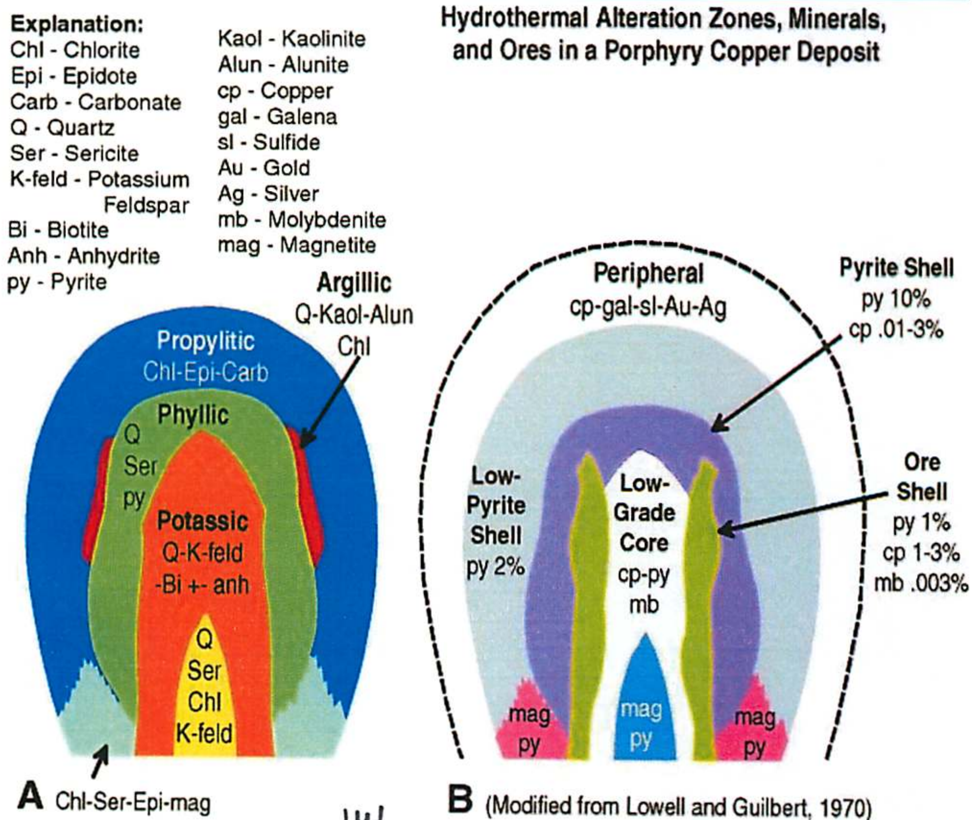


Figure 2: Porphyry copper deposit (Mars and Rowan, 2006)

History

- Silver was the basis of historical mining enterprises throughout Arizona.
- The first documented discovery of silver and copper was by the Spanish in 1598 near Jerome.
- Later documentation recorded mining activity in the southernmost portion of the state around 1750 in Ajo.
- Significant deposits of copper were noted (see Figure 3) but were not typically exploited as transportation was difficult prior the completion of the Southern Pacific Railroad in 1876. However, "high grading" and some processing to concentrate the ore at sites in Ajo, Clifton, and Jerome was underway by the completion of the railway.
- After the purchase of southern portion of the state in 1853, American miners started work on deposits discovered in Santa Cruz and Pima Counties.
- With the Gladstone Purchase came the acquisition of the dispute that became known as the Apache War, delaying development of the area. Some raids were occurring as late as 1924.
- By the 1870's significant development was underway throughout the state.
- Dedicated silver mining declined after the demonetization of silver in 1893.
- Large scale copper mining in the state took off in 1917 when the open pit mine near Ajo.

Processes

- Most of the mining done during the latter half of the 19th century was based on the underground method. Either a vertical shaft or a horizontal adit would be driven into the formation and branching stopes blasted outwards to follow to richest part of the formation. (see Figure 5)
- With the successful open pit at Ajo, open pit mining has become the preferred method of ore removal. (see Figure 6)
- Copper ore can be concentrated in two methods:
    - Froth Flotation: e.g: Lime, alcohol, pine oil, and potassium amyl xanthate are mixed in water and crushed ore is also introduced. Air is injected into the tank. The ionic ends of the xanthate collect the copper and the hydrophobic ends collect on the oily bubbles. These bubbles rise to the surface and flow off the top of the tank.
    - Leaching: Either in a vat or pile, a acidic mixture dependant on the ore chemistry is run through crushed ore selectively removing the desired mineral. In some cases, the resultant liquors can be introduced directly to the electrowinning process.

Current Controversy

- Mining processes are very water intensive by its nature as a working fluid.
    - The Rosement Mine south of Tucson has met with significant opposition due to effects on ground water usage; a column of water one acre in area and a mile high per year.
    - Opponents make the argument that mining creates undue demand on the areas water supply.
- Most mines proponents use the claim that mining brings jobs to an area.
- There is also significant opposition to mining in areas that are protected as parks, such as the Grand Canyon (Uranium mining).

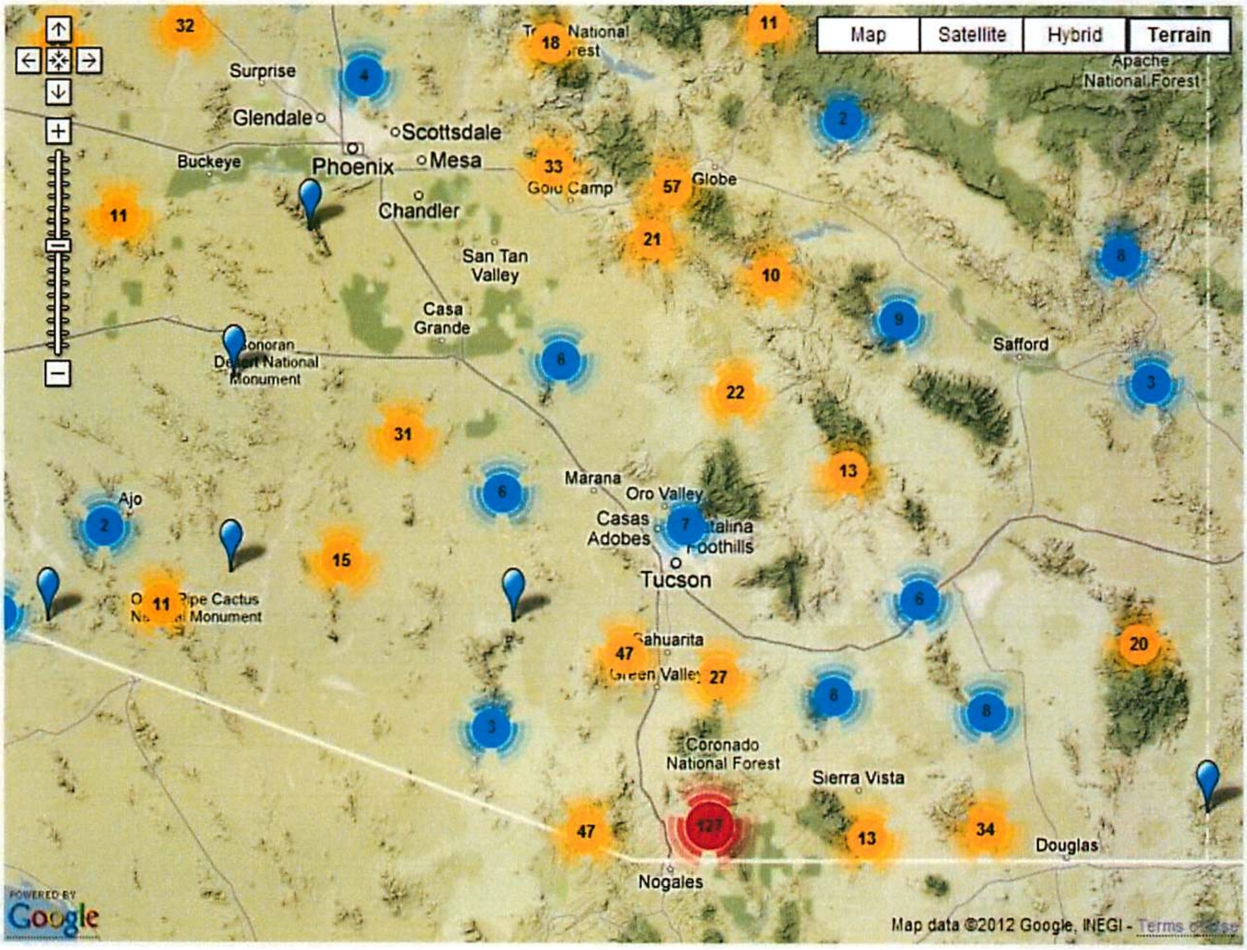
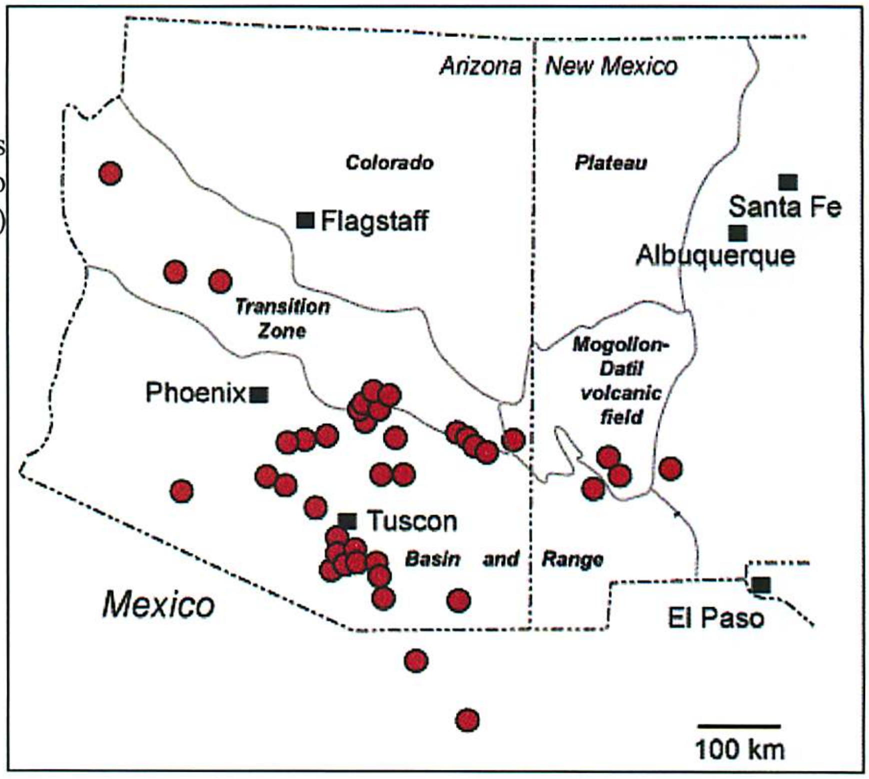


Figure 4: Mines of southern Arizona; the number in the circle denotes that that area has *N* mines

Figure 3: Porphyry copper deposits of Arizona and western New Mexico (Titley and Anthony, 1989)



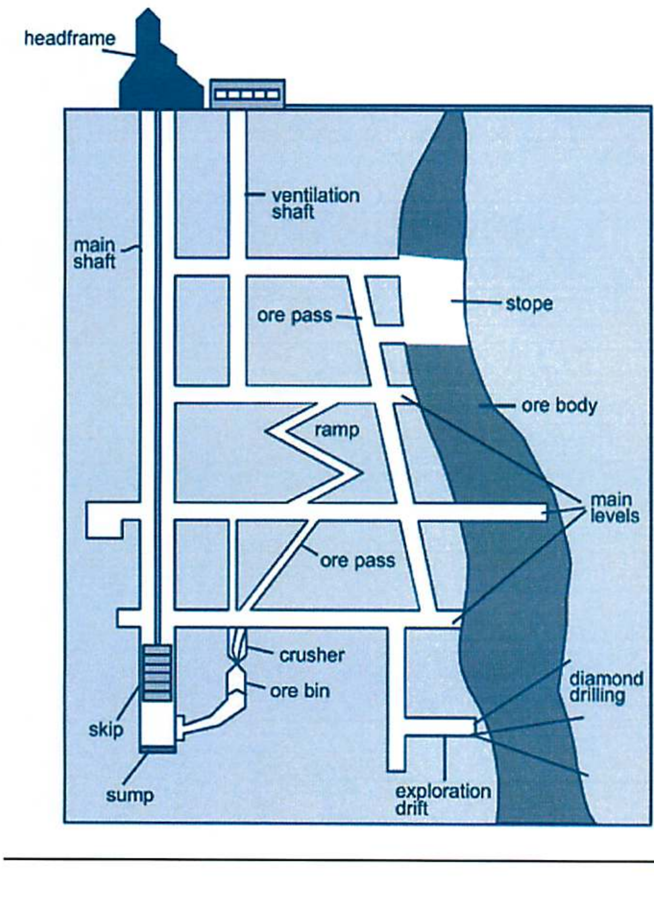


Figure 5: Typical underground mine layout. (from ec.g.ca/lcpe-cepa/)

Figure 6: Open pit mine near Ajo (Photo by Peter Kresan via pubs.usgs.gov/gip/deserts/minerals/)

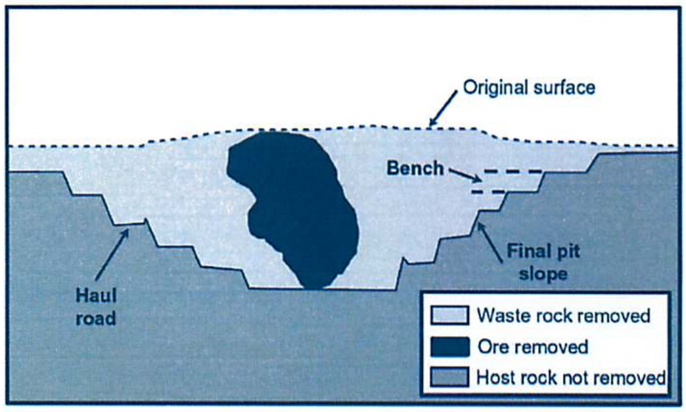


Figure 7: Typical open pit mine layout. (from ec.gc.ca/lcpe-cepa/)

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Find That Field Trip!

by Ali Bramson

(easy)

S	X	Y	E	L	L	O	W	S	T	O	N	E
C	D	D	E	C	H	E	L	L	Y	K	O	L
G	A	N	M	L	B	D	I	E	N	T	S	E
E	N	N	A	O	L	A	N	I	O	B	A	N
R	Y	C	Y	S	J	A	J	U	S	O	X	I
O	R	Y	R	O	E	A	V	A	C	U	E	T
N	E	R	R	E	N	T	V	H	U	N	T	N
I	R	W	X	S	I	L	I	E	T	D	T	E
M	C	H	I	R	I	C	A	H	U	A	S	S
O	C	I	X	E	M	W	E	N	W	R	E	N
F	F	A	T	S	G	A	L	F	D	Y	W	D
C	I	Y	Y	E	N	T	Y	V	I	S	L	S
N	O	Y	N	A	C	D	N	A	R	G	A	Y

baja
deathvalley
geronimo
mojave
tucson
yellowstone
canyonlands
dechelly
grandcanyon
newmexico
westtexas
chiricahuas
flagstaff
ktboundary
sentinel
whitesands

Find That Field Trip!

by Ali Bramson

(hard)

N	L	.	.	.	C	G	.	R	.	N	.	M	.
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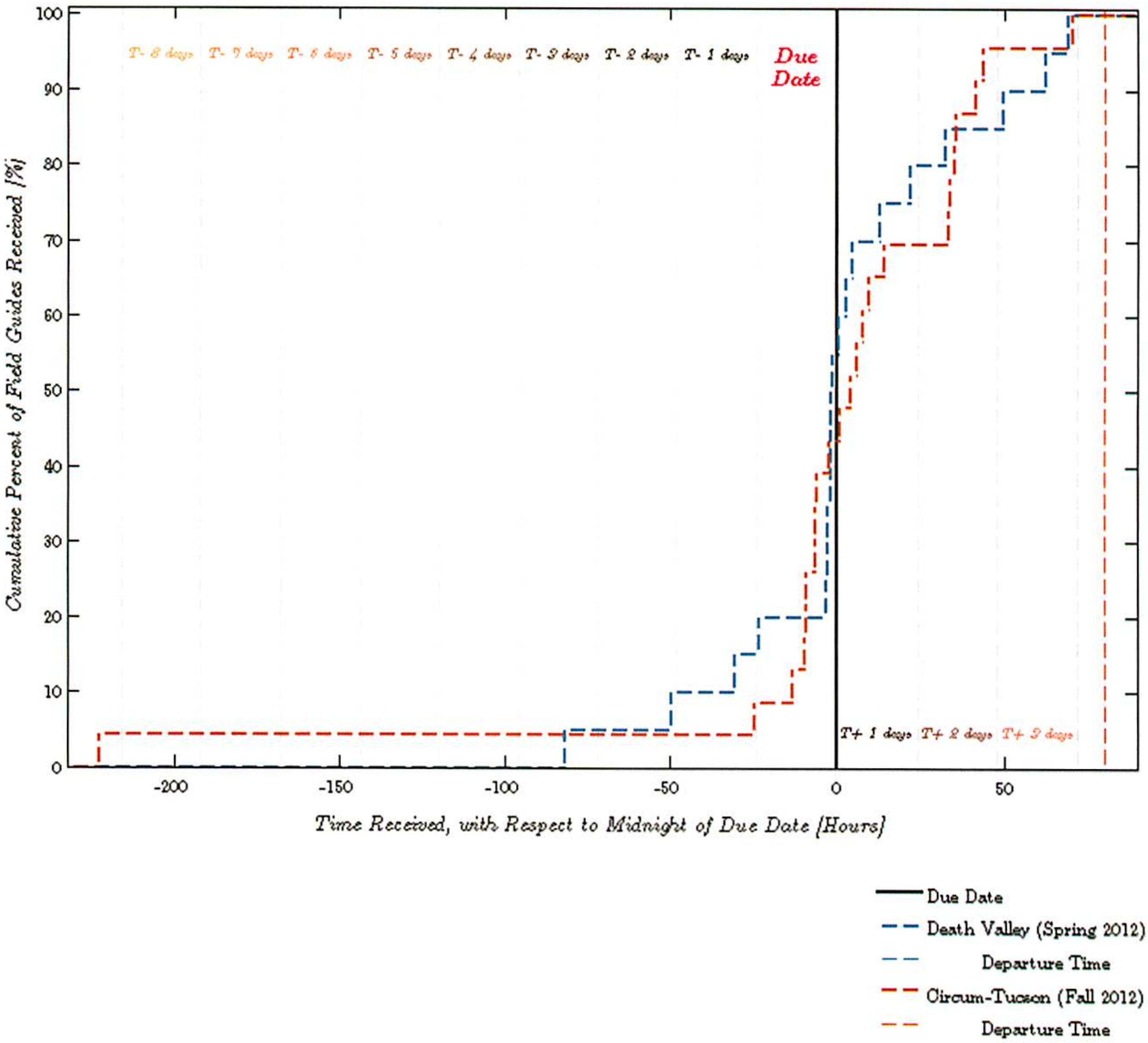
.	D	D	D	.	T	.	C	N	G	.	T	.	W
L	B	S	.	N	T	.	N	.	L	H	D	S	L
F	.	.	S	.	X	.	T	T	S	.	W	M	.

baja	canyonlands	chiricahuas	deathvalley
dechelly	flagstaff	geronimo	grandcanyon
ktboundary	mojave	newmexico	sentinel
tucson	westtexas	whitesands	yellowstone

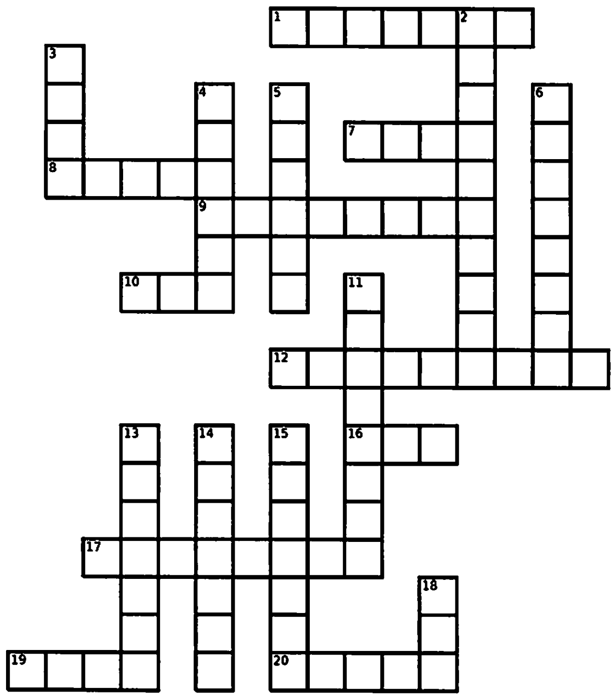
How good are grad students with field guide deadlines?*



**admittedly, for both field trips I personally told most students that the deadline was "soft"*

Nerds at the Movies

K Miller



Across

1 "__________!" - Sheldon Cooper, The Big Bang Theory

7 "I'm sorry, ________. I'm afraid I can't do that." - HAL, 2001: A Space Odyssey

8 "Face it ________, you just hit the jackpot!"–Mary Jane, Spider-Man

9 "Wait a minute, Doc. Ah... Are you telling me you built a time machine... out of a ____________?" - Marty McFly, Back to the Future

10 "Gentlemen, you can't fight in here! This is the ________ Room!" – President Merkin Muffley, Dr. Strangelove

12 "Nothing shocks me–I'm a ___________." - Indiana Jones, Indiana Jones and the Temple of Doom

16 "Goonies never say________." -Mike, The Goonies

17 "Take your ________ paws off me, you damn dirty ape!" – Taylor, Planet of the Apes

19 "Try not. Do, or do not. There is no try." - _________, The Empire Strikes Back

20 "There is no ________" - The Matrix

Down

2 "Strange women lying in ponds distributing swords is no basis for a system of _________. Supreme executive power derives from a mandate from the masses, not from some farcical aquatic ceremony." — Dennis the Peasant, Monty Python and the Holy Grail

3 "We're going to need a bigger________." – Chief Brody, Jaws

4 "One ring to rule them all, one ring to find them, one ring the bring them all, and in the darkness bind them. In the land of ________ where the shadows lie." –LOTR

5 "I don't believe there's a power in the 'verse that can stop ___________ from being cheerful. Sometimes you just wanna duct-tape her mouth and dump her in the hold for a month." – Malcolm Reynolds, Firefly

6 "Greetings,__________!" -Flynn, TRON

11 "...and it's not okay because if they take my stapler then I'll set the ________ on fire..." – Milton Waddams, Office Space

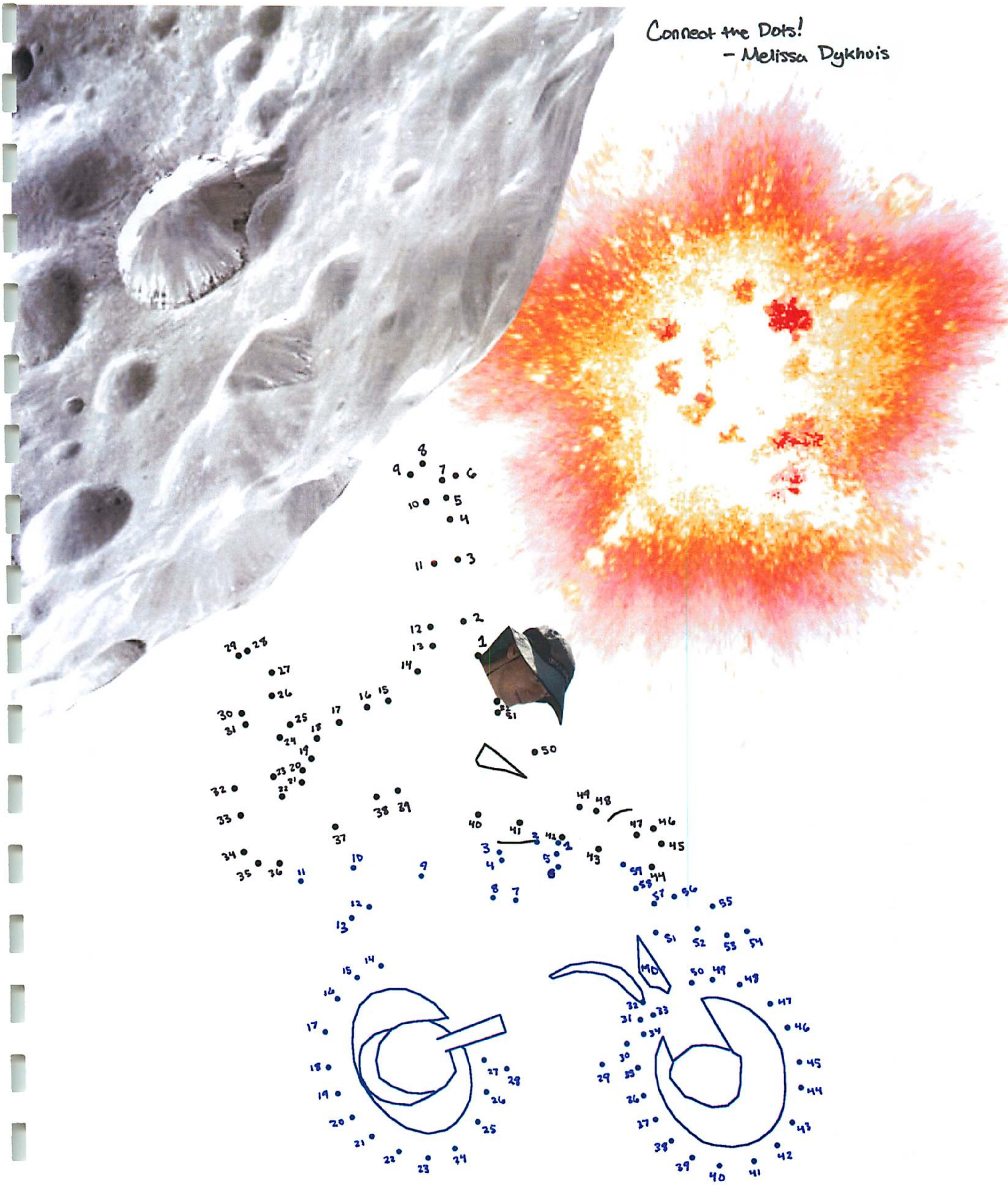
13 "My name is Inigo__________. You killed my father. Prepare to die!" -Inigo, The Princess Bride

14 "Well, let's say this _________ represents the normal amount of psychokinetic energy in the New York area. Based on this morning's reading, it would be a _________ thirty-five feet long, weighing approximately six hundred pounds." - Egon, Ghostbusters

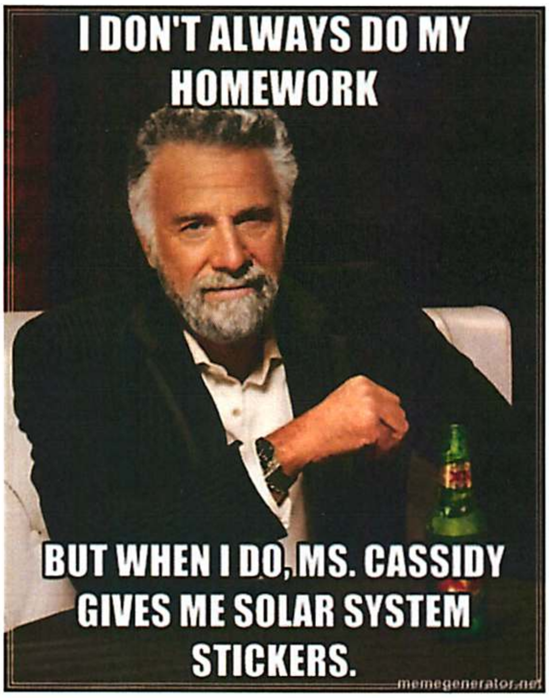
15 "WHY SO ________? Let's put a smile on that face" – The Joker, The Dark Knight

18 "Hey Vasquez, have you ever been mistaken for a _________?" "No, have you?" - Aliens

Connect the Dots!
– Melissa Dykhuis



Hello friends,
I wish I was on the field trip with you all. I thought I'd contribute a few things to the field guide for your amusement ☺
Love,
Meghan



Name that Asteroid!

I had my 5th and 8th graders submit an entry for the Planetary Society's Name that Asteroid! Contest to name 1999 RQ36. The name can be no more than 16 characters long and should be from mythology. They have to submit their name and a few sentences why they chose that name. Here are some samples of the 150+ collected.

"I think it should be called ***Shera*** because Osiris is a boy and we at least need one girl so I named it Shera." – 5th grader

"Just like in Greek myths where Griffins and other creatures were small compared to Zeus, asteroids are small compared to planets, so I think the asteroid should be called ***Griffin***." – 5th grader

"I think the asteroid should be called ***BoomDynamite*** because that's pretty cool." – 5th grader

I think the asteroid should be called ***Asterodite***. I was Aphrodite for Halloween and Asterodite sounds like asteroid. I think asteroids are beautiful and Aphrodite is the goddess of beauty and love. It is pronounced as-ter-o-die-tee." – 5th grader

"I think the asteroid should be named ***Willow Smith*** because she is an awesome singer and her music be so great it rocks outer space." – 5th grader

"I think it should be called ***Cyclops*** because it is a big ball of rock that looks like an eye ball. A big eye ball reminds me of a Cyclops eye so you should pick my name." – 5th grader

"I chose ***Eptnus*** because it's unexpected and sounds mythological. Plus it's got letters from the Earth, Pluto, Neptune, Uranus, and Saturn in the name." – 5th grader

"I want to name it ***Isis*** because she is Osiris' wife in Egyptian mythology. Osiris becomes king of the gods but Set the lord of evil [dun-dun-dun!] ticks Osiris and he dies. Isis goes after her husband's coffin while her son Horas battles Set. " – 5th grader

"***Physics Asteroid***. I could not really find any other name. This just came to me. I think this name will really fit." – 8th grader

"***Spock*** stands for space rock. I think the asteroid should be called Spock because the asteroid is a rock and is in space. Spock is also the name of a character in a space show." – 8th grader

"The asteroid should be called ***Xenon***. You can use xenon as a laser. It is unstable like as asteroid because an asteroid can hit earth one day. Finally we use it in nuclear fission in laboratories." – 8th grader

"I think having the name ***OSIRIS-REx's Baby*** would be the most unique. This will be the first asteroid that OSIRIS-REx visits, so it will be his first baby." – 8th grader

"***Hades2.0*** because Osiris is the Egyptian god of death and Hades is the Greek god of death." – 8th grader

"I picked the name ***Diamond of Fire*** because I like the mythological creature of the Phoenix. The bird is powerful like an asteroid is powerful when it makes a crater. The asteroid shape looks like a diamond, too." – 8th grader

"I think the asteroid should be called ***Cronos*** because he was an awesome greek god who was reborn as a lava monster. Lava monsters are big like asteroids. I would call the asteroid that." – 8th grader

"I think the asteroid should be called ***Prometheus820***. I loved the movie and I like that name. The number and the word sound really good together." – 8th grader

"I decided to call the asteroid ***Siren*** because the asteroid is luring us in to find out more information about it. Hopefully, it will not lead us to our deaths (or the death of OSIRIS-REx), but still will be one of the many things in space that fascinates us and that we find out more about." – 8th grader

"I would name the asteroid ***Dionysus*** because he is the god of win and the asteroid looks like a grape. There aren't any planets that represent food and food is awesome like space is awesome." – 8th grader

Ask a Planetary Scientist!

To give me ideas for a "Fact of the Day" that I do every day in physical geography class, at the end of a quiz I asked one class of 5th graders to write one question they would like to ask a Planetary Scientist. Can you answer them? Are you smarter than a 5th grader?

"What is your favorite planet and why?"

"What is the biggest asteroid?"

"Why can't you send more rockets into space so we can sail to the planets like pirates?"

"Did you want to be a planetary scientist even when you were little?"

"Do you like studying these things?"

"How many times do you have to do your experiments to make your results?"

"How do you know when a volcano will erupt?"

"What is the moon made of?

"Will anything interesting happen to planets soon (like blowing up or anything like that)?"

"Do you know how to work in a Planetarium?"

"Do planetary scientists get first dibs when a planet is being named?"

"How does the study of planetary science help us discover more about our own planet?"

"How can we improve the study of planetary science?"

"Are you married?"

"Can stars near Earth cause Black Holes and suck up the Earth and kill everyone?"

"How do you build telescopes to look so far?"

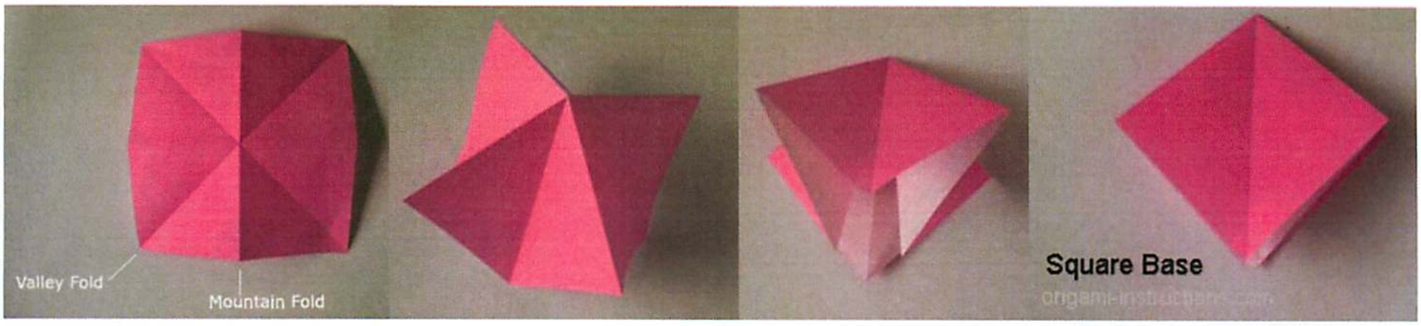
"When do meteor showers happen?"

"What is the tallest plant you've ever seen and how long did it take to grow?" (token Plant Science question)

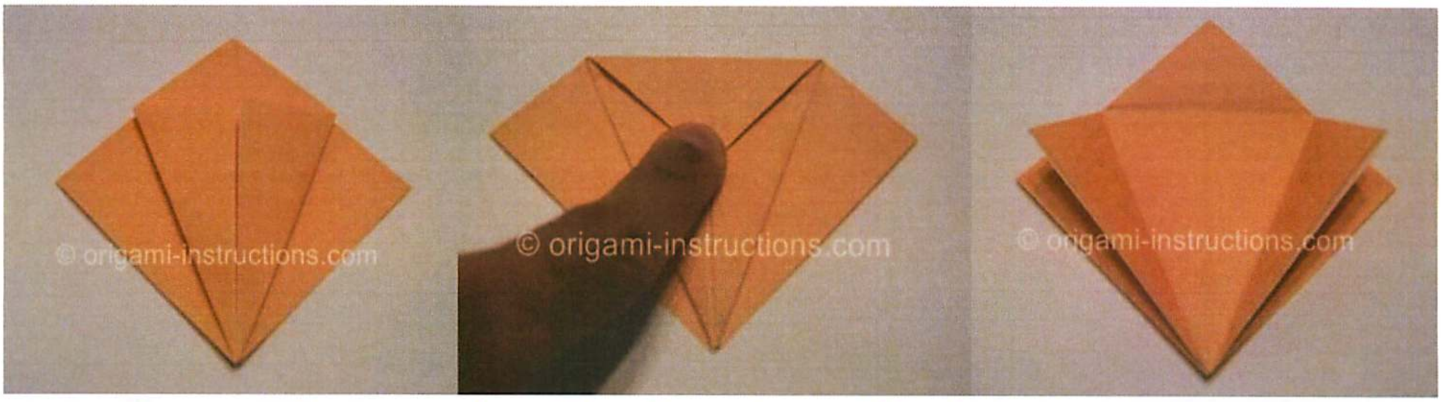
How to make an Origami Dinosaur (pt.1)

Follow the instructions below, and you can turn the attached piece of colored paper into a dinosaur! To start, rip out the colored paper and cut it into a square.
This follows instructions from: http://www.origami-instructions.com/origami-square-base.html

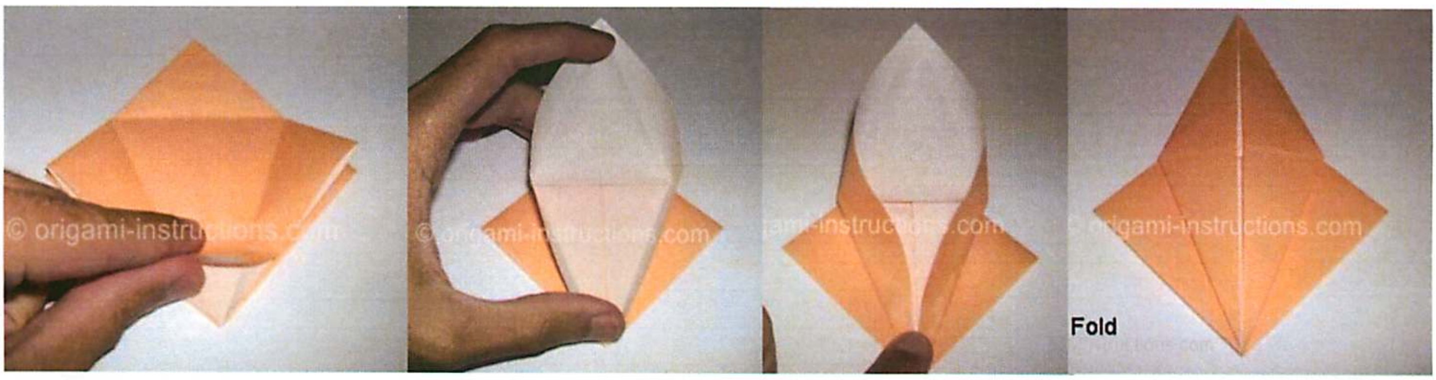
Fold the square along the diagonals, as well as on the North-South and East-West.
Collapse the square along these folds to make



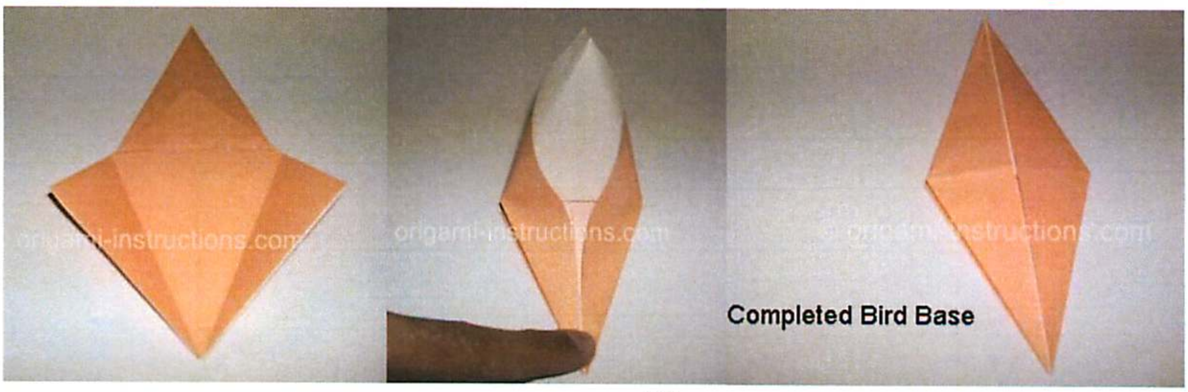
Fold the corners of this square base in toward the center. Make sure that the creases are good.



Now open up the upper-most layer of the well-creased square, folding the tip upward and flattening.

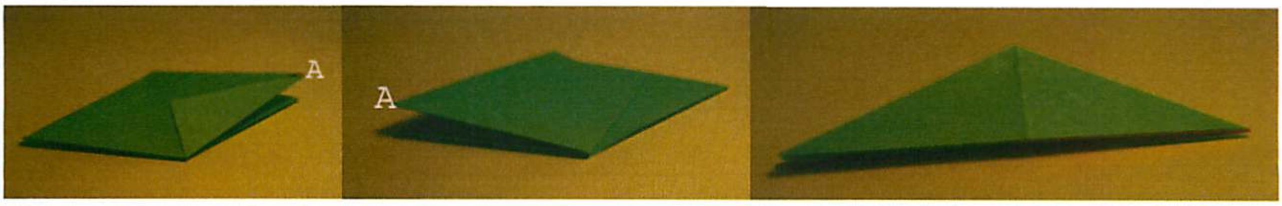


Flip the whole assembly over, and repeat the previous step for the other side of the origami.

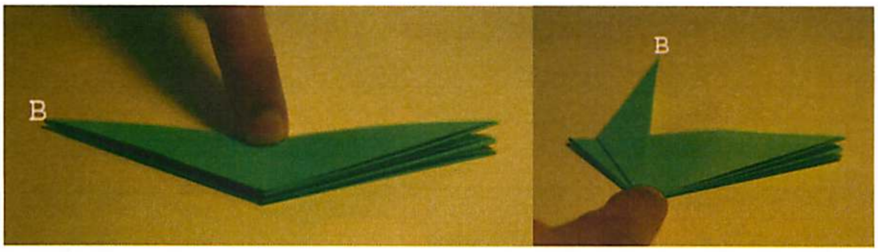


How to make an Origami Dinosaur (pt.2)

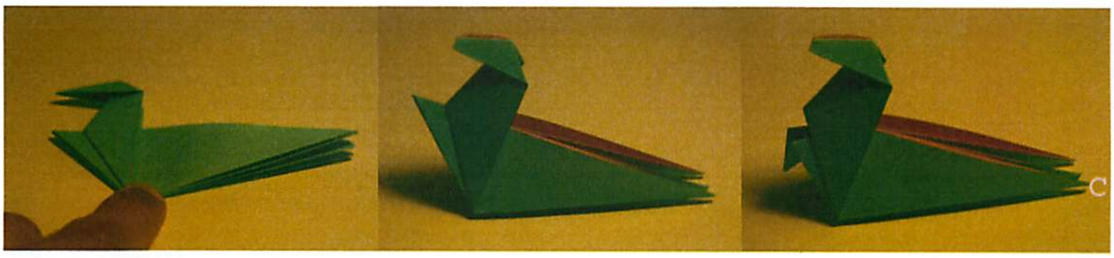
Fold corner A of the "bird base" to the left, as shown below. Then fold the assembly in half along the long axis.



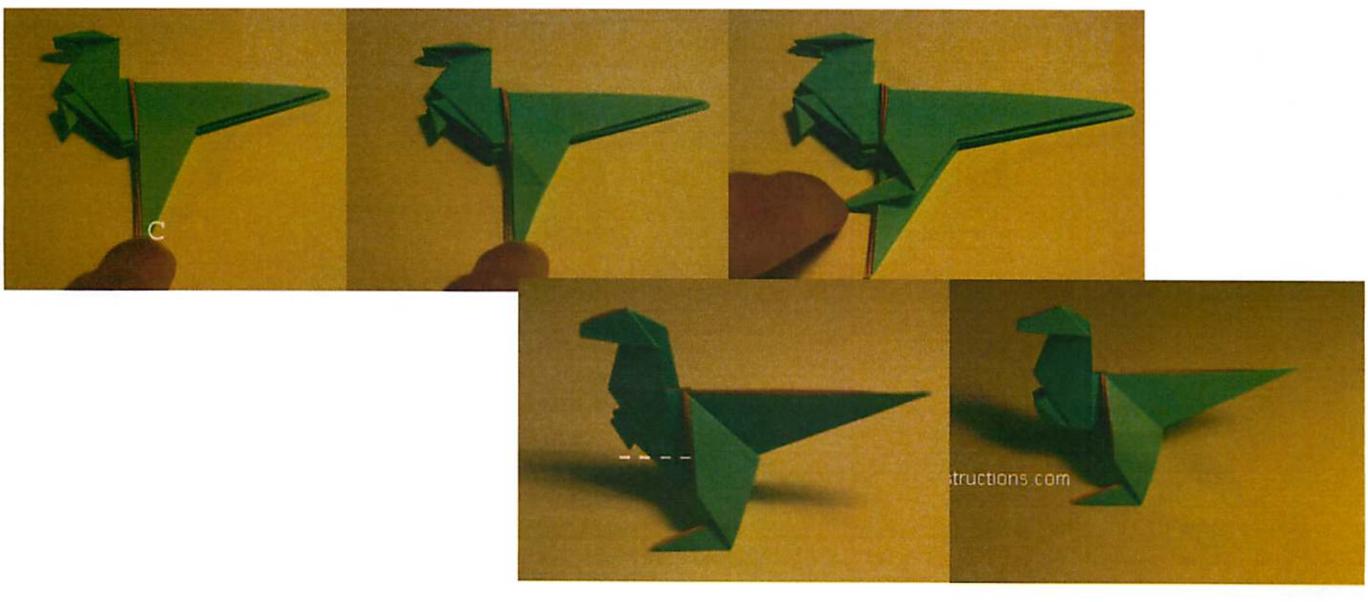
Rotate the assembly 180 degrees, and then do a reverse fold to create the dinosaur's neck.



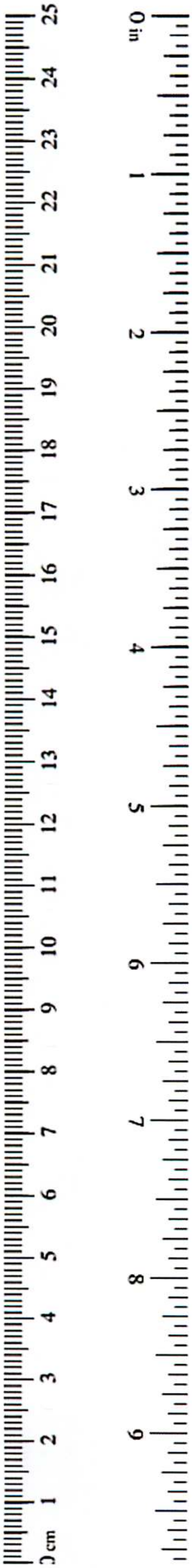
Perform another reverse fold to make the dinosaur's head. Further small folds can shorten the dinosaur's skull, and create downward pointing arms.



Fold down corner "C" (labeled in the last figure above), to form the dinosaur's leg. Repeat on the other side to get the second leg. Then crimp the legs to form the dinosaur's feet. To slim the body, you can fold the lowermost part of the body inside of itself.



You now have an origami dinosaur!



Scale bar