Letter from the Editor

Geology.
Heck yeah.

James Keane, editor
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Road log for PTYS 594 – All times are AZ times

Thursday 3/1/2012
7 AM Arrive at LPL loading dock with all our gear including breakfast, coffee, ice etc...
8 AM Depart LPL
   Drive north on Cherry -> west on Speedway -> enter I10 westbound
   Drive 238 miles to Quartzsite, take exit 19 (Riggles Ave) northbound route 95.

12.45PM Arrive Quartzsite – Lunch near here.

1.30PM Left onto Main Street then right onto route 95 north within Quartzsite.
   Drive 23 miles on the 95, turn left and drive another 12 miles. Cross the Colorado at Parker. Transition here to the 62, drive 18 miles. Turn right onto US route 95 and drive 48 miles. Join I40 westbound, drive 65 miles and take exit 78 for Kelbaker Rd.

5PM Drive north on Kelbaker Road for 14.5 miles.
   Turn left at Kelso Dunes Road and drive 4-5 miles.

   Optional Stop at good exfoliation site in the Granite Mountains.
   Take the third left off Kelbaker Road about 5.5 miles north of I40 (take county road 20731, drive ~3/4 of a mile).

5.30PM Camp: Kelso Dunes. Hear about booming dunes from Christa. Hike to the top if there’s time...
   Elevation 2500'. Sunset 6.44PM AZ time.
Road log for PTYS 594 – All times are AZ times

FRIDAY 3/2/2012

8 AM  Leave Camp. Sunrise 7:16AM. Backtrack to Kelbaker Road. Drive North to Baker for 43 miles. The road continues as the CA 127, drive another 83 miles. Turn left onto the CA 190W and go 18 miles. Turn left onto Furnace creek road and drive 13.1 miles (transition to Dante’s View road after 7.5 miles).

12.30  Dante’s View. Lunch + listen to James talk about the tectonic history of Death Valley and Cecilia & Meghan tag team a presentation on how Death Valley got its name.

2.00PM Drive back out to CA 190 (13 miles) and turn left and drive 7.6 miles.

2.45PM We’re beside Zabriskie Point where we can talk about the Gower’s gulch diversion. Stephanie will tell us about river profiles and how they readjust to changing circumstances.

3.15PM Leave Zabriskie Point. Drive 10 minutes to Bad Water road on the other side of the divide and see the changes being wrought on Gower’s Gulch fan.

4PM   Leave Gower’s Gulch fan. Drive 27 miles further on the CA 190 and stop at the side of the road to access the Mesquite Flat Dunefield (drive past the turn for Giotto canyon road by ~0.5 miles).

4.30PM Arrive at the dunes. Edge of the dunefield is ~100m from the road (along with the Giotto canyon mudflow). Bradley will tell us about dune migration while mudflows will be expounded upon by Beary. There’s a star dune ~1 mile from the road that Cecilia will describe, we’ll hopefully have time to walk out there too.

5.45  Leave the dunes, drive 11 miles further down the CA190 to Emigrant Campground. Hope for a campsite. If none then backtrack to Stovepipe Wells and suck up the RV fumes.

Road log for PTYS 594 – All times are AZ times

SATURDAY 3/3/2012

8 AM  Leave Camp. Sunrise 7:15AM.
Backtrack on CA 190 9 miles and turn right towards Mosaic Canyon. Drive 2.3
miles to the entrance to Mosaic Canyon. Probably with a bathroom break in
Stovepipe Wells.

8.45AM Mosaic Canyon: This is a good place to check out the alluvial fan and its
multiple terraces of varying age from Kat. Rock varnish distinguishes surfaces
of older age and the sordid story of research on this subject can be recounted
by Vic. Within the canyon we'll see the conglomerated breccia that it's famous
for and hear about canyon formation from Colin.

10AM Leave the Canyon and backtrack to the 190. Drive east until Scotty's Castle
Road (7 miles), turn left (north) and drive 34 miles. Turn left onto Ubehebe
Crater Road and drive 6 miles.

11.30 Arrive at Ubehebe crater and listen to Amber fill us in on how Phreatomagmatic
eruptions work. The it's time for lunch and enjoyment of the view!

1PM Leave Ubehebe crater.
Drive south on Racetrack Valley road for 27 miles (passing Tin mountain
landslide after 15.5 miles and Teakettle Junction after 19 miles). Estimate 90
minutes for this drive.

2.30 Arrive at Racetrack Playa.
Shane will muse about playa formation, after which we'll walk out to the
famously mysterious sliding rocks (~2km roundtrip). Catherine will fill us in on
what we know here.

4PM Leave Racetrack Playa
Drive back past Ubehebe Crater to Scotty's Castle Road, turn right and drive
half a mile until a left turn onto Mesquite Road. Drive 2 miles down Mesquite
Road to the campsite.

6.00PM Camp: Mesquite Spring campground. Elevation 1800’. Sunset 6.45PM AZ time.
Backup Camp: Stovepipe Wells. Elevation 0’.

Backup site takes an extra hour to get to – we must dance to appease the campsite
Gods (and perhaps take a small animal to sacrifice).
Road log for PTYS 594 – All times are AZ times

SUNDAY 3/4/2012

8 AM  Leave Camp. Sunrise 7:14AM. Backtrack 2 miles to Scotty’s Castle Road, turn right and drive 33 miles. Turn left onto CA 190 and drive 18 miles, turn right onto Badwater road and drive 8.6 miles to Ventifact Ridge.

9.40AM  Arrive at Ventifact Ridge. Look around and listen to Sarah to get the details.

10.15AM  Leave Ventifact Ridge. Drive 2.5 miles south to Salt Pool Road, turn right here and drive 1.3 miles.

10.30AM  Arrive Devil’s Golf Course. Look around and hear Meghan describe where the heck salt polygons come from.

11.15AM  Leave Devil’s Golf Course. Drive back to Badwater Road and a further 5.5 miles south to Badwater itself. Tourist stop – take pictures of the sea level sign etc... View Salt Pan differences from Devil’s golf course.

12PM  Leave Badwater. Drive south on Badwater Road 12.2 miles to Salt weathering site.

12.20PM  Lunch and a talk from Michelle about salt weathering.

1.30PM  Leave Salt weathering site. Drive 15 miles south to shoreline Butte. There’s a turnout/vista point on the west side of the road. Or drive 13.3 miles to the west-side road turnoff and drive west on that for ~1 mile. Seems like a 1 mile hike to the Butte either way. We’ll make this decision on the fly depending on the time.

2PM  Arrive at the Shoreline Butte Stop. Listen to Corey and Donna describe the waxing and waning of lake Manly and the shoreline features we can still see.

It’s 2hrs 15 minutes from here to the Cima Campsite. We’ll exit Death Valley via Jubilee Pass. Go a few more miles south on Badwater Road, take a left onto the 178 (east) and travel 25 miles. Turn right onto the 127 and travel 58 miles to Baker. The road continues as Kelbaker Road for another 15.3 miles. A small dirt road called Indian Springs Trail leads off to the left. We’ll take that for 1-2 miles before stopping to camp.

We should arrive in plenty of time for Youngmin to describe the Cima volcanic field (we’ll be right beside the freshest flow) – food for thought as we settle down for the last night.

5.00PM  Camp: Cima Volcanic Field. Elevation 2400’. Sunset 6.46PM AZ time.
Road log for PTYS 594 – All times are AZ times

MONDAY 3/5/2012

8 AM  Break Camp. Sunrise 7:12AM.

Nearby lava flows span a large range of ages. The flow surfaces degrade with age as Melissa can describe. A flow just to the north of us allowed researchers to recently figure out how desert pavement forms – prepare to be amazed by Gabriel’s description.

10 AM  Leave Cima Volcanics.

It’s 8 hours driving back to LPL. Stops and Lunch along the way means this is probably 9.5 hours minimum.

7:30PM Return to LPL. Sunset in Tucson 6:25PM

Participants

1. Atwood-Stone, Corey
2. Baker, Vic
3. Bray, Veronica
4. Byrne, Shane
5. Cassidy, Meghan
6. Chung, Youngmin
7. Dykhuis, Melissa
8. Elder, Catherine
9. Keane, James
10. Keske, Amber
11. Leung, Cecilia
12. Moats, Stephanie
13. Morrison, Sarah
14. Muro, Gabriel
15. O’Brien, Dave
16. Spitale, Joe
17. Thompson, Michelle
18. Van Laerhoven, Christa
19. Viola, Donna
20. Volk, Kat
21. Williams, Bradley
22. Xiao, Zhiyong (Beary)
The Night Sky

This night sky maps below are for Stovepipe Wells, on the night of Friday, March 3rd. All times are in Arizona times. Data from Heavens-Above.com.

March 2nd, 6:00 pm

March 3rd, 12:00 am
The Night Sky

This night sky map, and planet data below are for Stovepipe Wells, on the night of Friday, March 3rd. All times are in Arizona times. Data from Heavens-Above.com.

March 3rd, 6:00 am

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<th>Mercury</th>
<th>Venus</th>
<th>Mars</th>
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The magnitude system – for measuring the relative brightness of celestial objects. From http://www.astronomynotes.com/starprop/appmag.gif

Apparent brightnesses of some objects in the magnitude system.
The Night Sky

Satellite Passings, March 1st

Location: Kelso Dunes, 34.9108°N, 115.7311°W
Brightness cutoff (mag): 4.0

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<th>Azimuth</th>
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### Satellite Passings, March 2nd

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### Satellite Passings, March 3rd

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**Brightness cutoff (mag): 4.0**

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### Satellite Passings, March 4th

**Location:** Cima Volcanic Field, 35.1843°N, 115.8449°W  
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<td>19:56:54</td>
<td>20°</td>
<td>NE</td>
<td>19:56:54</td>
<td>20°</td>
<td>NE</td>
<td>19:52:57</td>
<td>18°</td>
<td>SE</td>
</tr>
<tr>
<td>Cosmos 2369</td>
<td>3.6</td>
<td>19:56:24</td>
<td>10°</td>
<td>SSW</td>
<td>20:02:03</td>
<td>74°</td>
<td>ESE</td>
<td>20:07:46</td>
<td>10°</td>
<td>NNE</td>
</tr>
<tr>
<td>ADEOS II</td>
<td>2.2</td>
<td>19:56:54</td>
<td>10°</td>
<td>SSE</td>
<td>20:01:58</td>
<td>51°</td>
<td>ENE</td>
<td>20:07:03</td>
<td>10°</td>
<td>N</td>
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<td>Meteor 2-5 Rocket</td>
<td>3.6</td>
<td>20:06:37</td>
<td>10°</td>
<td>N</td>
<td>20:12:15</td>
<td>77°</td>
<td>E</td>
<td>20:17:46</td>
<td>10°</td>
<td>SSE</td>
</tr>
<tr>
<td>SL-8 R/B</td>
<td>3.3</td>
<td>20:07:19</td>
<td>10°</td>
<td>NNE</td>
<td>20:10:52</td>
<td>83°</td>
<td>ESE</td>
<td>20:14:19</td>
<td>10°</td>
<td>S</td>
</tr>
<tr>
<td>Cosmos 1666</td>
<td>2.7</td>
<td>20:09:09</td>
<td>10°</td>
<td>S</td>
<td>20:13:10</td>
<td>71°</td>
<td>E</td>
<td>20:17:12</td>
<td>10°</td>
<td>NNE</td>
</tr>
<tr>
<td>Cosmos 540 Rocket</td>
<td>4.0</td>
<td>20:10:52</td>
<td>10°</td>
<td>SSW</td>
<td>20:15:53</td>
<td>61°</td>
<td>WWN</td>
<td>20:20:58</td>
<td>10°</td>
<td>N</td>
</tr>
<tr>
<td>Tiangong 1</td>
<td>0.2</td>
<td>20:14:46</td>
<td>10°</td>
<td>WWN</td>
<td>20:17:21</td>
<td>58°</td>
<td>WSW</td>
<td>20:17:21</td>
<td>10°</td>
<td>W</td>
</tr>
<tr>
<td>Cosmos 2082</td>
<td>3.6</td>
<td>20:21:19</td>
<td>30°</td>
<td>WWN</td>
<td>20:26:58</td>
<td>88°</td>
<td>ENE</td>
<td>20:30:05</td>
<td>28°</td>
<td>SSE</td>
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<td>GPS 2-04 Rocket1</td>
<td>2.9</td>
<td>20:29:39</td>
<td>10°</td>
<td>W</td>
<td>20:34:14</td>
<td>86°</td>
<td>N</td>
<td>20:34:30</td>
<td>80°</td>
<td>ENE</td>
</tr>
<tr>
<td>Cosmos 2056 Rocket</td>
<td>3.8</td>
<td>20:58:48</td>
<td>10°</td>
<td>NNW</td>
<td>21:03:13</td>
<td>61°</td>
<td>NW</td>
<td>21:03:13</td>
<td>10°</td>
<td>NW</td>
</tr>
</tbody>
</table>
**Figure 4. Generalized Stratigraphic Column, Death Valley Region**

**Quaternary**
- Fan gravel; silt and sand on floor of playas; less than 100 feet thick.
- Fan gravel; silt and sand buried under floor of playas; perhaps 2,000 feet thick.
- Cemented fan gravel with interbedded basaltic lavas; gravels cut by veins of calcite (Mexican onyx); perhaps 1,000 feet thick. Distalts, pollen.
- Cemented gravel, silt and silty deposits; various salts, especially borates; 3,000 feet thick. Scour faults.
- Cemented gravel; playa deposits; much volcanic debris; 5,000 feet thick.
- Scour faults.
- Cemented gravelly stream deposits; 3,000 feet thick. Vertebrates, tithanerites, etc.
- Granitic intrusions and volcanics.
- 8,000 feet of metasediments and volcanics. Ammonites, smooth-shelled gastropods, belemnites, and baccacods.
- Conglomerate, limestone, and some shale. Conglomerate contains cobbles of limestone of Mississippian, Pennsylvanian, and Permian age. Limestone and shale contain spherical chert nodules. Thickness uncertain on account of faulting; estimated 3,000 feet or more. Beds with fusulinds.
- Mostly shale, some limestone abundant. Spherical chert nodules. Thickness uncertain because of faulting; estimated 750 feet.

**Tertiary**
- Missing as 1 unit. Tim Mountain Limestone 1,000 feet thick, is black with thin-beded lower member and thick-beded upper member. Unnamed limestone formation, 275 feet thick, consists of interbedded chert and limestone in thin beds and in about equal proportions. Mixed brachiopods, corals, and crinoids.
- Limestone in light and dark beds 1-10 feet thick give striped effect on mountainsides. Two quartzite beds, each about 3 feet thick, near base; several sandstone beds 200-1,000 feet above base. Top 200 feet is well-beded limestone and quartzite. Total thickness uncertain because of faulting; estimated 2,000 feet. Brachiopods abundant, stromatoporoids.
- Thick-beded, fine- and evaginuous dolomite; mostly light color. Thickness 300-1,950 feet. Crinoid stems abundant, including large types. Fossiliferous. Massive black dolomite; 400-800 feet thick. Steptesiolamid corals, brachiopods, large numbers of small brachiopods. Massive quartzite, with thin-beded quartzite at base and top; 230 feet thick.
- Dolomite, with some limestone, at base; shale unit in middle; massive dolomite at top. Thickness, 1,500 feet. Abundant large gastropods in massive dolomite at top. In lower beds, Orthid brachiopods.
- Highly fossiliferous shale member 100 feet thick at base; upper 1,200 feet is dolomite in thick alternating black and light bands about 100 feet thick. Total thickness of formation, 1,200-1,500 feet. In upper part, gastropods, in basal 100 feet, trilobite and brachiopods. Thick-beded and massive dark-colored dolomite; thin-beded limestone member 500 feet thick, 1,000 feet below top of formation; brown-weathering shale. Thickness, 1,000 feet above bed. Upper one fossiliferous, about 250 and 500 feet, respectively, below unit. Shaly and silty members with limestone member transitional between underlying clastic formations and overlying carbonates 1,000 feet thick. Numerous trilobite and brachiopod beds in lower part yield fragments of ameloid trilobites. Thick, mostly massive and granulated due to shearing; locally in beds 6 inches to 2 feet thick; not much crossbedding. Thickness more than 150 feet; variable because of shearing.
- Basal unit is well-beded quartzite above 1,650 feet thick; shale unit above this 520 feet thick contains lowest ameloid limestones in section top unit of dolomite and quartzite 400 feet thick.
- Well-beded quartzite in beds 1-5 feet thick comprising thick members of quartzite 700-800 feet thick separated by 500 feet of purple shale; cross-beded conspicuous in quartzite. Maximum thickness about 2,000 feet.
- Shale, olive brown and purple. Basal member 400 feet thick is interbedded dolomite and quartzite, with pebble conglomerate. Limestone, thin dolomite near middle and at top. Thickness more than 4,000 feet.
- Southern Panamint Range, dolomite in indistinguishable beds; 1,000 feet. Scolithus? Clastic dolomite-quartzite rock abundantly crossbedded, thinbedded, and arkose sandstone and siltstone.
- Conglomerate (diamictite) and sandstone, and subordinate siltstone and shale; graded beds and giant clasts common; may be as much as 5,000 feet.
- Conglomerate (diamictite) and sandstone, generally poorly banded, thinbedded, and arkose sandstone; well laminated to massive.
- Blue-grey cherty dolomite, well laminated to massive; oolitic lenses and beds common; forms prominent ridges; 1,000 feet. Outcrops are to the west.
- Mixed sediments rocks; sandstone, siltstone, shale, dolomite; minor conglomerate.
- Diabase, chert, and stromatolitic limestone.
- Siliceous dolomite, talc deposits where diabase intrudes dolomite.
- Mudstone.
- Paleoshaly sandstone and siltstone.
- Arkose conglomerate, sandstone and siltstone.
- Metasedimentary rocks, mostly granitic gneiss.

Modified from Hunt, 1966, and Trexel, 1982
EXPLANATION FOR FAULT MAP OF THE DEATH VALLEY-AMARGOSA VALLEY REGION, CALIFORNIA-NEVADA

Mesozoic thrust fault, barbs on upper plate

Cenozoic thrust fault, barbs on upper plate

Cenozoic strike-slip fault

Cenozoic oblique-slip fault, bar and ball on down-thrown side

Other Cenozoic faults, predominantly normal, locally vertical, bar and ball on down-thrown side

Unshaded area is underlain by undeformed to slightly deformed Quaternary and Pliocene units.

Shaded area is underlain by deformed Pleistocene and Pliocene units and all older units.

Gregory & Baddeley, 1988
Figure 12. Generalized geologic map of Death Valley, California showing major faulting and location of "turtlebacks". Turtlebacks are: Badwater (BW), Copper Canyon (CC), Mormon Point (MP), and Tucki Mountain (TM). Other features: Virgin Spring (VS), Furnace Creek (FC), Amargosa fault (AF), and Desert Hound anticline (DH). (see article by Sheehan in this volume.)
## Mineralogy

### Dark-Colored minerals

<table>
<thead>
<tr>
<th>Hardness</th>
<th>Cleavage</th>
<th>Physical Properties</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent or good</td>
<td>Dark gray, blue-gray or black. May be streaked. Cleavage in 2 planes at nearly right angles. Muscovite. Hardness 2.</td>
<td>Plagioclase Feldspar</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Brown, green or red. Cleavage in 2 planes at nearly right angles. Exsolution Lamellae. Hardness 6.</td>
<td>Potassium Feldspar</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Opalescent, black. Cleavage at 90°. Hardness 5.</td>
<td>Hornblende (Amphibole)</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Opalescent, gray, hexagonal prisms with curved faces. Hardness 9.</td>
<td>Corundum</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Grey, brown or green. Grainy texture. Massive or blocky prisms and crystals. Translucent to translucent. Hardness 7.</td>
<td>Quartz</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Opalescent, brown. Waxy luster. Hardness 7.</td>
<td>Jasper</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Opalescent, black. Waxy luster. Hardness 7.</td>
<td>Garnet</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Colorless, purple, green, yellow, blue. Acicular prisms. Hardness 4.</td>
<td>Fluorite</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Green, splint along 1 excellent cleavage plane. Hardness 3.</td>
<td>Chlorite</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Black to dark brown. Split along 1 excellent cleavage plane. Hardness 4.5.</td>
<td>Biotite mica</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Opalescent, gray or yellow. Silky or grayish luster. Hardness 3.5.</td>
<td>Serpentine</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Opalescent, white, gray or green. Can be scratched with fingernail. Soft feel. Hardness 1.</td>
<td>Sunstone</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Opalescent, dark or light brown. Hardness 5-6.</td>
<td>Hematite</td>
<td></td>
</tr>
</tbody>
</table>

### Light-colored minerals

<table>
<thead>
<tr>
<th>Hardness</th>
<th>Cleavage</th>
<th>Physical Properties</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent or good</td>
<td>White or gray. Cleavage in 2 planes at nearly right angles. Striations. Hardness 6.</td>
<td>Plagioclase Feldspar</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Orange, brown, white, gray, green or pink. Cleavage in 2 planes at nearly right angles. Exsolution Lamellae. Hardness 8.</td>
<td>Potassium Feldspar</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Pale brown, white or gray. Long slender prisms. Cleavage in 1 plane. Hardness 6-7</td>
<td>Sillimanite</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Opalescent, red, gray, white, hexagonal prisms with striated flat sides. Hardness 9.</td>
<td>Cornelian</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Colorless, white, grey or other colors. Grainy texture. Massive or hexagonal prisms and pyramids. Transparent or translucent. Hardness 7.</td>
<td>Quartz</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Colorless, white, yellow, light brown. Transparent or translucent. Lustrous or metallic. Cleavage oblique. Hardness 7.</td>
<td>White-Milky, Yellow-Citrine, Pink- Rose</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Pale silver gray. Twinning on c-axis. Transparent or translucent. Hardness 7.</td>
<td>Olivine</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Colorless, white, yellow, blue, green. Excellent cleavage in 3 planes. Breaks into dodecahedrons. Efflorescence in HCl. Hardness 3.</td>
<td>Calcite</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Colorless, white, yellow, blue, green. Excellent cleavage in 3 planes. Breaks into dodecahedrons. Efflorescence in HCl only if powdered. Hardness 3-4.</td>
<td>Dolomite</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>White with hints of brown. Short tubular crystals or mica. Very lustrous. Hardness 3-5.</td>
<td>Barite</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Colorless, white or grey. Massive or tubular crystals, blades or needles. Can be scratched by fingernail. Hardness 2-2.5</td>
<td>Gypsum</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Colorless, white. Cubic crystals. Silky sheen. Hardness 2-2.5</td>
<td>Halite</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Colorless, purple, green, yellow, blue. Acicular crystals. Hardness 4.</td>
<td>Fluorite</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Colorless, yellow, brown. Splint along 1 excellent cleavage plane. Hardness 2-2.5</td>
<td>Maslovite mica</td>
<td></td>
</tr>
<tr>
<td>Excellent or good</td>
<td>Yellow crystals or acicular masses. Hardness 1.5-2.5.</td>
<td>Sulfur</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Opalescent, gray or yellow. Silky or greyish luster. Hardness 3.5-4.</td>
<td>Serpentine</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Opalescent, gray or green. Can be scratched with fingernail. Soft feel. Hardness 1.</td>
<td>Sunstone</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Opalescent, dark or light brown. Hardness 5-6.</td>
<td>Hematite</td>
<td></td>
</tr>
<tr>
<td>Poor or absent</td>
<td>Opalescent, white or yellow. Can be scratched with fingernail. Soft feel. Hardness 2-2.5</td>
<td>Kyanite</td>
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</table>

### Metallic

<table>
<thead>
<tr>
<th>Hardness</th>
<th>Streak</th>
<th>Physical Properties</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Gray</td>
<td>Brass yellow</td>
<td>Pyrite</td>
<td></td>
</tr>
<tr>
<td>Brown</td>
<td>Dark gray-black, attracted to magnet</td>
<td>Magnetite</td>
<td></td>
</tr>
<tr>
<td>Silvery black to black tarnishes gray</td>
<td>Chrome</td>
<td>Chrome</td>
<td></td>
</tr>
<tr>
<td>Silvery gray, black, or brick red</td>
<td>Hematite</td>
<td>Hematite</td>
<td></td>
</tr>
<tr>
<td>Brass yellow, tarnishes dark brown or purple</td>
<td>Chalcopyrite</td>
<td>Chalcopyrite</td>
<td></td>
</tr>
<tr>
<td>Iridescent blue, purple, or copper red, tarnishes dark purple</td>
<td>Bornite</td>
<td>Bornite</td>
<td></td>
</tr>
<tr>
<td>Silvery gray, tarnishes dull gray</td>
<td>Galena</td>
<td>Galena</td>
<td></td>
</tr>
<tr>
<td>Dark gray to black, can be scratched with fingernail</td>
<td>Graphite</td>
<td>Graphite</td>
<td></td>
</tr>
</tbody>
</table>

### Chemical Group

<table>
<thead>
<tr>
<th>Oxides minerals</th>
<th>ANIONIC SPECIES</th>
<th>EXAM PLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen, O²⁻</td>
<td>Hematite, Fe³⁺: Magnetic; Fe³⁺</td>
<td></td>
</tr>
<tr>
<td>Sulphur, S²⁻</td>
<td>Pyrite, FeS²⁻</td>
<td></td>
</tr>
<tr>
<td>Carbonates</td>
<td>Carbonate, CO₃²⁻</td>
<td>Calcium, CO₃²⁻: Dolomite, CaMgCO₃₂.</td>
</tr>
<tr>
<td>Silicates</td>
<td>Silicate, SiO₄²⁻: Terraces</td>
<td>Rubidium, (SiO₄)⁻²: Terraces, (SiO₄)⁻²: Terraces</td>
</tr>
<tr>
<td>Structural Subgroups of the Silicates</td>
<td>Framework, Si₄O₁₈ or (Al₂Si₆O₁₈)</td>
<td>Quartz, SiO₂: K-Feldspar, K₂O₃: Fe₂O₃: MgO: SiO₂</td>
</tr>
</tbody>
</table>
| Exafs, Si₄O₁₈ | }

### Notes

- The table provides a comprehensive overview of minerals, their properties, and hardness ratings.
- The metallic section lists streaks and physical properties for different types of minerals.
- The chemical group section includes examples of oxides, carbonates, and silicates with their corresponding anionic species and examples.
**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 (L) – 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 (L) – as well as the percent composed of matrix (mud & silt). Regions based upon field data.
Classification Scheme for Sedimentary Rocks

<table>
<thead>
<tr>
<th>Classification Scheme for Sub-Conglomerates and Sub-Breccias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme based on percent of a rock composed of: gravel or pebbles (size &gt; 2 mm), sand (2 mm &gt; size &gt; 1/16 mm), and mud (size &lt; 1/16 mm).</td>
</tr>
</tbody>
</table>

Gravel/Pebbles

- Well-sorted Conglomerate or Breccia
- Muddy Conglomerate or Breccia
- Sandy Conglomerate or Breccia
- Pebby Mudstone
- Pebbly Wacke
- Pebby Arkite
- Mud
- Sand

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

![Very angular, Angular, Sub-angular, Sub-rounded, Rounded, Well rounded](image)

**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

![Percentage Diagrams](image)
Figure 5.13 The Udden Wentworth grain size scale and millimeter-to-phi conversion chart. (After Lewis, 1924: 50; by permission of Chapman and Hall, London.)

From Prothero and Schwab, 2004
**Sedimentary Rocks**

### 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

<table>
<thead>
<tr>
<th>Principle Allochems in Limestone</th>
<th>Limestone Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal Grains (Bioerlatics)</td>
<td></td>
</tr>
<tr>
<td>Ooids</td>
<td></td>
</tr>
<tr>
<td>Peloids</td>
<td></td>
</tr>
<tr>
<td>Intraerlatics</td>
<td></td>
</tr>
<tr>
<td>Limestone formed in place</td>
<td></td>
</tr>
</tbody>
</table>

- Cemented by Sparite
- Cemented by Micritic Matrix

### 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)

<table>
<thead>
<tr>
<th>Of the allochems, less than 10% are larger than 2 mm</th>
<th>Of the allochems, greater than 10% are larger than 2 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contains carbonate mud</td>
<td>Matrix supported</td>
</tr>
<tr>
<td>Grain supported</td>
<td>Grain supported</td>
</tr>
<tr>
<td>Less than 10% grains</td>
<td>Organisms acted as baffles</td>
</tr>
<tr>
<td>More than 10% grains</td>
<td>Organisms are encrusting and binding</td>
</tr>
<tr>
<td>Mudstone</td>
<td>Organisms building a rigid framework</td>
</tr>
<tr>
<td>Wackestone</td>
<td></td>
</tr>
<tr>
<td>Packstone</td>
<td></td>
</tr>
<tr>
<td>Grainstone</td>
<td></td>
</tr>
<tr>
<td>Floatstone</td>
<td></td>
</tr>
<tr>
<td>Rudstone</td>
<td></td>
</tr>
<tr>
<td>Bafflestone</td>
<td></td>
</tr>
<tr>
<td>Bindstone</td>
<td></td>
</tr>
<tr>
<td>Framestone</td>
<td></td>
</tr>
</tbody>
</table>
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).

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).

* If rock has > 40% mafic minerals, then it is a gabro. 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 Aphanitic Igneous Rocks

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

Aphanitic rocks are hard to classify due to the lack of visible minerals. However, you may still be able to 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).
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.

Other Useful Terminology for Naming Igneous Rocks:

Obsidian: black volcanic glass, formed by extremely rapid solidification of melt.

Vitrophyre: black volcanic glass (like obsidian), but with the presence of phenocrysts (included mineral grains).

Porphritic: a rock texture where there are phenocrysts of at least two distinct grain sizes.

Types of Tephra (Pyroclasts)

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

Bowen’s Reaction Series

Bowen’s reaction series shows the order in which minerals crystallize out of a melt. From http://en.wikipedia.org/wiki/File:Bowen%27s_Reaction_Series.png
### Metamorphic Rocks

**Classification Scheme for Metamorphic Rocks**

Based upon texture and mineralogical composition.

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

### Mineralogy for Metamorphic Rock Facies

#### Facies

<table>
<thead>
<tr>
<th>Facies</th>
<th>Definitive Mineral Assemblages in Mafic Rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zeolite</td>
<td>zeolites: especially laumontite, wairakite, analcime (in place of other Ca-Al silicates such as prehnite, pumpellyite and epidote)</td>
</tr>
<tr>
<td>Prehnite-Pumpellyite</td>
<td>prehnite + pumpellyte (+ chlorite + albite)</td>
</tr>
<tr>
<td>Greenschist</td>
<td>chlorite + albite + epidote (or zoisite) + actinolite ± quartz</td>
</tr>
<tr>
<td>Amphibolite</td>
<td>hornblende + plagioclase (Clinopyroxene, Andesine) ± garnet</td>
</tr>
<tr>
<td>Granulite</td>
<td>orthopyroxene + clinopyroxene + plagioclase ± garnet</td>
</tr>
<tr>
<td>Blueschist</td>
<td>glaucophane + lawsonite or epidote/zoisite (+ albite ± chlorite ± garnet)</td>
</tr>
<tr>
<td>Eclogite</td>
<td>pyroxspite garnet + omphacitic pyroxene (± kyanite ± quartz), no plagioclase</td>
</tr>
<tr>
<td>Contact Facies</td>
<td>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</td>
</tr>
</tbody>
</table>
**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

**Typical Mineral Changes in Progressive Metamorphism**
Along with the Barroonian zones of metamorphism for reference. From Winter, 2010
Types of Faults


Some jargon notes: strike-slip faults are also sometimes referred to as transform or wrench faults. Low angle reverse faults (<45 degrees) are frequently called thrust faults. Real faults can combine all of these senses of motion (and even rotation).

Hanging Wall vs. Foot Wall

These terms are frequently used when describing faulting. In a normal fault, the footwall moves up. In a reverse fault the footwall moves down. From Davis and Reynolds, 1996
Types of Folds

All rock layers are originally deposited horizontally - though they can later be deformed due to tectonic forces. The two general types of folds are synclines (convex side up) and anticlines (convex side down). If the overlying strata is not younger than the underlying strata (or not known), then this may mean the entire system has been rotated over. In this case, we use the terms synform and antiform. Folds can be subdivided into even further different shapes (images at right). Figures from Davis and Reynolds, 1996.

Types of Unconformities

Unconformities are gaps in the stratigraphic record.

Disconformity
Unconformity between parallel layers of sedimentary rock, with an erosional surface between.

Angular Unconformity
Strata are deposited on rotated, and eroded layers.

Nonconformity
Unconformity from the deposition of sedimentary rocks on eroded metamorphic or igneous rocks.

Paraconformity
When successive strata are parallel, and there is little to no evidence of an erosional surface – the unconformity looks like a bedding surface.
# Geologic Map & Stratigraphic Section Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Contact, showing dip where trace is horizontal, and strike and dip where trace is inclined</td>
</tr>
<tr>
<td>2</td>
<td>Contact, located approximately (give units)</td>
</tr>
<tr>
<td>3</td>
<td>Contact, located very approximately, or conjectural</td>
</tr>
<tr>
<td>4</td>
<td>Contact, concealed beneath unmarked units</td>
</tr>
<tr>
<td>5</td>
<td>Contact, gradational (optional symbol)</td>
</tr>
<tr>
<td>6</td>
<td>Fault, non-specific, well located (optional symbols)</td>
</tr>
<tr>
<td>7</td>
<td>Fault, non-specific, located approximately</td>
</tr>
<tr>
<td>8</td>
<td>Fault, non-specific, assumed (existence uncertain)</td>
</tr>
<tr>
<td>9</td>
<td>Fault, concealed beneath mapped units</td>
</tr>
<tr>
<td>10</td>
<td>Fault, high-angle, showing dip (left) and approximate dips</td>
</tr>
<tr>
<td>11</td>
<td>Fault, low-angle, showing approximate dip and strike and dip</td>
</tr>
<tr>
<td>12</td>
<td>Fault, high-angle normal (D or null and bar on downthrown side)</td>
</tr>
<tr>
<td>13</td>
<td>Fault, reverse (R on upthrown side)</td>
</tr>
<tr>
<td>14</td>
<td>Fault, high-angle strike-slip (example is left lateral)</td>
</tr>
<tr>
<td>15</td>
<td>Fault, thrust (T on upthrow side)</td>
</tr>
<tr>
<td>16</td>
<td>Fault, low-angle normal or detachment (D on downthrown side)</td>
</tr>
<tr>
<td>17</td>
<td>Fault, low-angle strike-slip (example is right lateral)</td>
</tr>
<tr>
<td>18</td>
<td>Fault, low-angle, overturned (tenth in direction of dip)</td>
</tr>
<tr>
<td>19</td>
<td>Optional sets of symbols for different age groups of faults</td>
</tr>
<tr>
<td>20</td>
<td>Fault zone or shear zone, width to scale (dip and other accessory symbols may be added)</td>
</tr>
<tr>
<td>21</td>
<td>Faults with arrows showing plunge of rolls, grooves or slickensides</td>
</tr>
<tr>
<td>22</td>
<td>Fault showing bearing and plunge of net slip</td>
</tr>
<tr>
<td>23</td>
<td>Point of inflection (bar) on a high-angle fault</td>
</tr>
<tr>
<td>24</td>
<td>Points of inflection on a strike-slip fault passing into a thrust</td>
</tr>
<tr>
<td>25</td>
<td>Fault intruded by a dike</td>
</tr>
<tr>
<td>26</td>
<td>Faults associated with veins</td>
</tr>
<tr>
<td>27</td>
<td>Anticline, showing trace and plunge of hinge or crest line (specify)</td>
</tr>
<tr>
<td>28</td>
<td>Syncline (as above), showing dip of axial surface or trough surface</td>
</tr>
<tr>
<td>29</td>
<td>Fold (as above), located approximately</td>
</tr>
<tr>
<td>30</td>
<td>Fold, conjugate</td>
</tr>
<tr>
<td>31</td>
<td>Fold, concealed beneath mapped units</td>
</tr>
<tr>
<td>32</td>
<td>Asymmetric folds with steeper limbs dipping north (optional symbols)</td>
</tr>
<tr>
<td>33</td>
<td>Anticline (top) and syncline, overturned</td>
</tr>
<tr>
<td>34</td>
<td>Antiformal (inverted) syncline</td>
</tr>
<tr>
<td>35</td>
<td>Synformal (inverted) anticline</td>
</tr>
<tr>
<td>36</td>
<td>Antiform (top) and synform (stratigraphic sequence unknown)</td>
</tr>
<tr>
<td>37</td>
<td>Separate dome (left) and basin</td>
</tr>
<tr>
<td>38</td>
<td>Culmination (left) and depression</td>
</tr>
<tr>
<td>39</td>
<td>Anticline and syncline, showing shapes in horizontal section</td>
</tr>
<tr>
<td>40</td>
<td>Vertically plunging anticline and syncline</td>
</tr>
<tr>
<td>41</td>
<td>Monocline, south-facing, showing trace of axial surfaces</td>
</tr>
<tr>
<td>42</td>
<td>Steeply plunging monocline or flexure, showing trace in horizontal section and plunge of hinges</td>
</tr>
<tr>
<td>43</td>
<td>Plunge of hinge lines of small folds, showing shapes in horizontal section</td>
</tr>
<tr>
<td>44</td>
<td>Strike and dip of beds or bedding</td>
</tr>
<tr>
<td>45</td>
<td>Strike and dip of overturned beds</td>
</tr>
<tr>
<td>46</td>
<td>Strike and dip of beds where stratigraphic tops are known from primary features</td>
</tr>
<tr>
<td>47</td>
<td>Strike and dip of vertical beds or bedding (dot is on side known to be stratigraphically the top)</td>
</tr>
<tr>
<td>48</td>
<td>Horizontal beds or bedding (as above)</td>
</tr>
<tr>
<td>49</td>
<td>Approximate (typically estimated) strike and dip of beds</td>
</tr>
<tr>
<td>50</td>
<td>Strike of beds exact but dip approximate</td>
</tr>
<tr>
<td>51</td>
<td>Trace of single bed, showing dip where trace is horizontal and where it is inclined</td>
</tr>
<tr>
<td>52</td>
<td>Strike and dip of fossiliferous beds (optional symbols)</td>
</tr>
<tr>
<td>53</td>
<td>Strike of vertical foliation</td>
</tr>
<tr>
<td>54</td>
<td>Horizontal foliation</td>
</tr>
<tr>
<td>55</td>
<td>Strike and dip of bedding and parallel foliation</td>
</tr>
<tr>
<td>56</td>
<td>Strike and dip of joints (left) and dikes (optional symbols)</td>
</tr>
<tr>
<td>57</td>
<td>Vertical joints (left) and dikes</td>
</tr>
<tr>
<td>58</td>
<td>Horizontal joints (left) and dikes</td>
</tr>
<tr>
<td>59</td>
<td>Strike and dip of veins (optional symbols)</td>
</tr>
<tr>
<td>60</td>
<td>Vertical veins</td>
</tr>
<tr>
<td>61</td>
<td>Horizontal veins</td>
</tr>
<tr>
<td>62</td>
<td>Bearing (trend) and plunge of lineation</td>
</tr>
<tr>
<td>63</td>
<td>Vertical and horizontal lineations</td>
</tr>
<tr>
<td>64</td>
<td>Bearing and plunge of cleavage-bedding intersection</td>
</tr>
<tr>
<td>65</td>
<td>Bearing and plunge of cleavage-cleavage intersections</td>
</tr>
<tr>
<td>66</td>
<td>Bearings of pebble, mineral, etc. lineations</td>
</tr>
<tr>
<td>67</td>
<td>Bearing of lineations in plane of foliation</td>
</tr>
<tr>
<td>68</td>
<td>Horizontal lineation in plane of foliation</td>
</tr>
<tr>
<td>69</td>
<td>Vertical lineation in plane of vertical foliation</td>
</tr>
<tr>
<td>70</td>
<td>Bearing of current from primary features; from upper left: general; from cross-bedding; from flutes casts; from imbrication</td>
</tr>
<tr>
<td>71</td>
<td>Bearing of wind direction from dune forms (left) and cross-bedding</td>
</tr>
<tr>
<td>72</td>
<td>Bearing of ice flow from striations (left) and orientation of striations</td>
</tr>
<tr>
<td>73</td>
<td>Bearing of ice flow from drumlins</td>
</tr>
<tr>
<td>74</td>
<td>Bearing of ice flow from crenel and tail forms</td>
</tr>
<tr>
<td>75</td>
<td>Spring</td>
</tr>
<tr>
<td>76</td>
<td>Thermal spring</td>
</tr>
<tr>
<td>77</td>
<td>Mineral spring</td>
</tr>
<tr>
<td>78</td>
<td>Asphaltic deposit</td>
</tr>
<tr>
<td>79</td>
<td>Bituminous deposit</td>
</tr>
<tr>
<td>80</td>
<td>Sand, gravel, clay, or placer pit</td>
</tr>
<tr>
<td>81</td>
<td>Mica, quartz, or open pit</td>
</tr>
<tr>
<td>82</td>
<td>Shaft: vertical, inclined, and abandoned</td>
</tr>
<tr>
<td>83</td>
<td>Adit, open (left) and inaccessible</td>
</tr>
</tbody>
</table>
Booming Dunes
Christa Van Laerhoven

Booming dunes emit sound at 70 – 110 Hz (with higher harmonics present) when sand avalanches down its leeward side. The booming happens near the crest of the dune where the sand is very close to the angle of repose (~30°). These dunes have also described as “burping” or “humming” and this phenomenon is known to happen at more than 40 sites, located all over the world. Note, however, that “booming” dunes are distinct from “squeaking” dunes, whose noise has a much higher frequency (~1000 Hz).

The frequency emitted can change over the duration of the booming event (Fig 1). However, it tends to be very clean, that is, only one frequency and its higher harmonics are emitted (Fig 2).

Figure 1 (left): Microphone recording of a booming dune. From Hunt et al. (2010).

Figure 2 (bottom): a) Microphone recording of a booming dune. b) Recording of the F2 note from a cello. From Hunt et al. (2010).
Sand Characteristics for Booming Dunes

- **Dry**: Recent rain will prevent booming. In laboratory tests (using sand from booming dunes) exposure to moisture will silence the sand, and noise making can be restored by heating the sand to drive off that moisture.

- **Narrow size frequency distribution**: In other words, the sand was well sorted. Booming dune sands are relatively lacking in both coarse and fine grains.

- **Narrow range of average grain diameter**: These have been measured to be 0.18 to 0.32mm, which is lower than average for dunes in general. Though it had been previously been suggested that the booming frequency depends on the grain size (Bagnold 1966), there is no evidence to support this (Fig 3).

- **Smooother particles**: As noted by Lindsay et al. (1976), the booming sand particles appear to be smoother on the scale of 1μm than those in non-booming dunes (Fig 4).

*Figure 3 (top): Boom frequency vs average grain diameter. The frequency appears to have no dependence on the grain diameter. From Hunt et al. (2010).*

*Figure 4 (right): A comparison of booming (a-c) and non-booming (d-f) sands. Scales: a and d: 500μm; b and e: 200μm; c and f: 40μm. From Lindsay et al. (1976).*
The Dune as a Waveguide

Dunes have layers with varying levels of compaction. The top layer has low seismic velocities and the lower layers have higher seismic velocities (Fig 5).

Upon energy input (from avalanching sand), this layered structure allows the dune to act as a waveguide for seismic body waves (Fig 6). The special case where the angle of incidence is the critical angle (as calculated from Snell's law: $\phi_c = \arcsin(c_1/c_2)$, where $c_1$ is the seismic speed in the surface layer and $c_2$ is that in the substrate) the waveguide experiences maximal excitation. In this case, successive waves constructively interfere and because the seismic speed in the atmosphere ($c_0$) is greater than that in the surface layer ($c_1$) the horizontal transmission in the waveguide (the dune) is coupled to that of the upper medium (the air).

References


Figure 5 (right): Seismic velocities in a booming dune on the leeward side near the crest a) during the summer and b) during the winter. In the summer layers are separated by sharp boundaries, whereas in the winter the change of seismic velocity with depth is much smoother. From Hunt et al. (2010).
Figure 6 (left): The dune as a waveguide. The seismic velocities are $c_0$, $c_1$, and $c_2$ for the atmosphere, surface layer, and substrate, respectively. From Hunt et al. (2010).
The Tectonic History of Death Valley

Regional Tectonics

Death Valley is located between two major tectonic regimes (see Figure #1):

→ The East Pacific Rise: a major oceanic spreading ridge & transform fault system. The spreading ridge (which created the Gulf of California), extends up to the Imperial Valley in Southern California (south of Death Valley), but the transform fault system associated with it (the San Andreas) extends up to the off the coast of northern California.

→ The Basin and Range Province: a vast range of the Western United States dominated by alternating horsts and grabens defined by normal faulting – indicative of large scale extension.

The History of the History of Death Valley Tectonics

Detailed geologic field work of Death Valley didn’t begin until the 1930’s. See Figure #2 for a geologic map of the Death Valley area.

→ Noble (1941) described Death Valley essentially as a syncline, modified by normal faulting – rather than a graben, which is defined by normal faulting. He particularly noted the interesting Amargosa Thrust Fault and Chaos – which is a jumbled mosaic of relatively small fault blocks, with older basement rocks overlying younger units.

→ Curry (1938a) mapped what he called “Turtlebacks”, which are smooth, curved topographic and structural mile-scale features. They were plunging anticlinal and synclinal forms of metamorphic and intrusive igneous rocks – characteristic of the mid-crust. He hypothesized these features to result from massive thrust faulting.

→ Hill (1954) – who had just published a classic paper on the San Andreas Fault – started to piece together the importance of strike-slip faulting throughout Southern California. Hill and Wright (1954) introduced the idea that Death Valley itself was a strike-slip fault, and that the Valley was a “fault trough” (with the fault buried under Quaternary deposits in the Valley).

→ Stewart (1967) correlated facies and isograds in the region, and proposed ~80 km of right-lateral displacement on the Death Valley-Furnace Creek fault zone. Oakes (1987) found evidence for ~35 km of right lateral strike-slip movement in the Death Valley fault zone by correlating alluvial fan gravels with their source areas.

→ Burchfiel and Davis (1966) proposed that Death Valley itself was caused by the “pull-apart” action of the Death Valley-Furnace Creek fault system.
Current Understanding of Death Valley Tectonics

As is typical in science, the correct answer (or at least our current understanding of it) was a combination of all of the previous work. Death Valley evolved by two major mechanisms over two time scales.

→ **Extension along a thrust fault (metamorphic core complex?):** Between 18-5 Ma, low angle detachment faults allowed for extension in the region. The particular style here is occasionally referred to as a metamorphic core complex – in which a very low angle detachment fault allows for the exhumation and tilting of fault blocks from the mid-crust (see Figure #3).

→ **Extension along a strike-slip fault:** By 3 Ma, the East California Shear Zone developed, and the modern topography of Death Valley formed as a pull-apart basin. This right-lateral shear caused extension, resulting in a lowering of topography.

References


Generalized fault map of the western United States showing the major tectonic features which surround Death Valley, California. See text for explanation.
Generalized geologic map of Death Valley, California showing major faulting and location of "turtlebacks". Turtlebacks are: Badwater (BW), Copper Canyon (CC), Mormon Point (MP), and Tucki Mountain (TM). Other features: Virgin Spring (VS), Furnace Creek (FC), Amargosa fault (AF), and Desert Hound anticline (DH).

- **Tertiary intrusives**
- **Jura-Triassic metavolcanics**
- **Faults and inferred faults**
- **Areas between ranges**: Quaternary alluvium, fan, terrace, lake and salt deposits
Diagram illustrating development of evolving shear zone during lithospheric extension. A: Configuration of crust prior to onset of extension in crystalline basement and overlying sedimentary and volcanic cover. Depth of distended crust is about 20 km with no vertical exaggeration. B: Configuration of distended crust after about 20% extension (from A) and isostatic uplift. Section is balanced. Lower plate rocks are drawn upward and out from beneath upper plate rocks. Mylonitic gneisses formed below crustal levels indicated by dash-dot line are transported to higher structural levels where they are retrograded and cataclastically deformed. After Davis et al. (1966)

Who Put the Death in Death Valley?
Meghan Cassidy and Cecilia Leung

1848 Gold Rush
- Gold discovered at Sutter's Mill in California.
- The '49ers
- Salt Lake City → Great Basin Desert → Sierra Nevada

The Old Spanish Trail
- The San Joaquin Company arrived late in October 1849. They had heard about the Old Spanish Trail, a route that went around the south end of the Sierra Nevada and was safe to travel in the winter.
- The "short cut" to Walker Pass would cut 500 miles from their journey.
- 20 wagons departed from Captain Hunt's group & from the Old Spanish Trail near present day town of Enterprise, Utah.

The "Short Cut"
- Many obstacles
- Lost after two months since leaving the Old Spanish Trail
- Snow storm → Death Valley
- Panamint Mountains

From Furnace Creek, two groups diverged...

A. The Jayhawkers

B. The Bennett-Arcan Party
- Sent two young men over the mountain to get supplies.
- the men took nearly a month
- Two families with children had patiently remained
- As they left, a woman proclaimed "Goodbye, Death Valley," giving the valley its morbid name.

Leaving Death Valley
- It took another 23 days to cross the Mojave Desert and reach the safety of Ranch San Francisco in Santa Clarita Valley.
- The so called "short cut" that had lured the Lost '49ers away from Captian Hunt's wagon train had proved to take four months and cost the lives of many men through the entire ordeal.

River Profiles and Knickpoint Migration

River profiles are characterized as having steep slope angles at its source, with a decreasing slope angle as it approaches sea level. Generally, the river cuts further down towards the base level (sea level) for decreasing altitude, and begins to cut laterally outwards as well in the lower areas. By the time the river reaches near sea level, the water is flowing along an almost flat surface as it meanders towards the sea. A schematic of a long river profile is shown below in Figure 1, while Figure 2 is a river profile for the Fish River.

![Figure 1: Simplified long river profile showing the upper, middle, and lower altitudes.](image1)

A knickpoint describes a location in a river profile in which the channel slope has a sharp change (which is often manifested as waterfalls). Knickpoint migrations are a result of a process called river rejuvenation. When the base level of a river falls, the river profile readjusts itself. As a result, it begins to cut down to its new base level with renewed energy (since it has more gravitational potential energy to cause vertical erosion). This begins at sea level and progresses upstream by headward erosion until a new equilibrium profile is reached. Figure 3 shows a schematic of this process.

![Figure 2: River profile for the Fish River, which matches the above schematic fairly well.](image2)
Stephanie Moats  
PTYS 594

Figure 3: Knickpoint migration cartoon. The dashed lines show past base levels that were higher than the present base level. Note that knickpoints from older base levels are higher than knickpoints from younger base levels.

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Accessed February 26, 2012
Dune Migration by Bradley Williams

There are two major methods of sand movement, saltation and surface creep. Since the majority of sand grains are small low mass grains, then primary mode of transportation is saltation.

![Diagram of sand movement](image)

Figure 1: Illustration of sand movement.

Saltation

This is when wind traveling faster than the fluid threshold (which Bagnold defines as the wind velocity necessary to begin saltating), picks up sand grains and carries them downwind until the weight of the sand grain causes the grain to drop out of the flow and crash into the sandy surface. This impact releases more grain particles into the flow of wind which continues the act of saltating. However, if the surface is hard enough, an impact will be avoided and thus the grain will bounce and continue downwind until surface hardness decreases or the small grains path meets a larger rigid body, i.e. larger pebble or small rock. This leads us into the second form of transportation for sand dunes, surface creep.

Creep

This explanation begins at the grain-pebble collision. The momentum carried by the small sand grain is transferred to the larger pebble and thus allowing creep. If enough grains collide with the pebble then the pebble or rock may begin to roll or creep. This process is much slower than saltation and lowers the distance traveled by the sand.
Suspension

When sand is near its minimum size, smaller than grains and approaching particle size, the wind carries it within the flow high above the surface where its mass has minimal effect on the trajectory of the particle. Suspension is the cause of the large dust clouds seen in desert wind storms.

Dune Formation

Some people don’t necessarily realize that dune formation also occurs on small scales. In dry, sandy environments, sand movement due to the wind generates ripples in the flat sandy surface. This is caused from varying sand grain and pebble size, and the variation of surface hardness and roughness. This makes the sandy desert surface unstable. Saltation varies with pebble and grain size creating ridges where larger grains accumulate into build-up deposits, i.e. the perceived ripples. This surface roughness created by the differing sized deposits decreases saltation on the downwind side of the ridge. This is described as a saltation shadow, in which creep occurs more steadily than saltation.

Figure 2: Small scale dune formation in the form of ripples in the Mesquite Valley.

On a large scale, when a large sand field exists, high velocity winds increase saltation. Saltation generates drag due to the high density of sand particles mixed with the air. Drag increases downwind and the particles slow down and begin accumulating. This accumulation eventually forms mounds in which more particles accumulate on the downwind side of the mound generating a steep leeward face. Saltation dramatically decreases on the leeward side resulting in increasing dune height.

Dune Migration

Now that we know how the dune developed we can understand how many of the same actions result in the movement or migration of the dune. If we imagine the velocity profile in figure 1, approaching the dune, then we see how erosion begins. The wind acts a fluid, and through fluid mechanics, it is
understood through the Bernoulli equation that a high pressure zone develops at the base of the dune on the windward side. This is where erosion begins. Sand then begins the process of moving up the dune where saltation also continuously occurs. At the peak of the dune, the flow separates and becomes turbulent and circulation in the flow develops on the leeward side of the dune where mixing now occurs. It is on the leeward side of the dune that sand begins to deposit. The resulting deposition builds up the leeward face of the dune until the angle of repose is reached. This angle is the maximum steepness for which the dune is stable. The name pretty much explains it; a slip face is the maximum steepness of the leeward face in which the friction force is stronger the force due to the mass of the sand, avalanches or dune collapses occur when this angle is greater than the angle of repose. Dunes continue to migrate by erosion and deposition caused by steady wind flow in front of the dune and the turbulent flow from separation at the top of the dune. This is very typical for Transverse and Barchan dune types. However, the ideas are relevant to almost all dune types with respect to wind speeds and directions.

Figure 3: Illustration of Dune Migration caused from wind as evident by the wind streamlines.

References:


Mudflows on the Earth, Mars and Titan

Zhiyong Xiao

1. Definition of mudflows

A mudflow is a type of very viscous, hyper-concentrated sediment flow. It is a rapid mass movement (> 1 km/hr) of mud formed from loose soil and water.

Mudflows are characterized by a sufficiently high concentration of non-cohesive particles, e.g., silts and calys (sediment size < 0.0625 mm). Mudflows exhibit high viscosity and yield stress, can travel long distances and leave lobate deposits on alluvial fans. Mudflow deposits are poorly sorted and they have abrupt and well-defined edges and irregular surfaces.

Fig. 1 (A) shows a schematic illustration of a mudflow. (B) is a small mudflow on the Earth. Mudflows always occur on steep slopes over 10°.
2. Factors contributing to mudflows

The behavior of a mudflow is a function of the fluid matrix properties (i.e. density, viscosity, and yield stress), channel geometry (roughness and constrictions), exposed slope, and surface roughness. The volume and properties of the fluid matrix govern flow hydraulics, flow cessation, and runout distances of mudflows. The fluid matrix properties are usually dependent on sediment concentration, size fraction, and clay content. The fluid properties change dramatically as they flow down alluvial fans or steep channels (Fig. 1). Usually, the peak concentration of sediment during a mudflow event is about 45%, and the average sediment concentration is between 20% and 35% (Table 1).

Table 1. Mudflow behavior as a function of sediment concentration (O'Brien).

<table>
<thead>
<tr>
<th>Sediment Concentration</th>
<th>Flow Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>by Volume *</td>
</tr>
<tr>
<td>Landslide</td>
<td></td>
</tr>
<tr>
<td>0.65 - 0.80</td>
<td>0.83 - 0.91</td>
</tr>
<tr>
<td>0.55 - 0.65</td>
<td>0.76 - 0.83</td>
</tr>
<tr>
<td>Mudflow</td>
<td></td>
</tr>
<tr>
<td>0.48 - 0.55</td>
<td>0.72 - 0.76</td>
</tr>
<tr>
<td>0.45 - 0.48</td>
<td>0.69 - 0.72</td>
</tr>
<tr>
<td>Mud Flood</td>
<td></td>
</tr>
<tr>
<td>0.40 - 0.45</td>
<td>0.65 - 0.69</td>
</tr>
<tr>
<td>0.35 - 0.40</td>
<td>0.59 - 0.65</td>
</tr>
<tr>
<td>0.30 - 0.35</td>
<td>0.54 - 0.59</td>
</tr>
<tr>
<td>0.20 - 0.30</td>
<td>0.41 - 0.54</td>
</tr>
<tr>
<td>Water Flood</td>
<td>&lt; 0.20</td>
</tr>
</tbody>
</table>
3. Triggering of mudslides

Mudflows can be triggered by:
- Rainfall: In small watersheds (< 5 mi²), smaller rain events (i.e., 10-year or 25-year storm event) are more likely to cause mudflows than larger events such as the 100-year flood. It is because large floods provide too much water for the available sediment supply, surging then occurs with debris frontal waves.
- Snowmelt.
- High levels of ground water flowing through cracked bedrock.
- Volcanoes: Sidoarjo mud flow (Lusi), Mount St. Helens. Mudflows are called Larhar at this situation.

4. Mudflows on Mars and Titan

Surface water has been suggested to exist on Mars for decades. Mudflow features are widely observed on Mars. In general, melting snow by volcanoes (Fig. 2A) and melting water by seasonal temperature change are suggested to be the triggering mechanics.

Fig. 2 (A) Interpreted mud flows near the foot of Ascraeus Mons' shield (HRSC image h2032_0001). (B) Mudflows and gullies on Mars formed between August 1999 and September 2005. HiRISE image PSP_001846_1415 located at 38.4 S, 96.8 E.

Cryovolcanoes on Titan erupt volatiles such as water, ammonia and methane. Methane rain is supposed to occur on Titan and river channels and lakes exist as well. Mudflows on Titan are widely supposed to be caused by mud volcanoes and methane.
rains.

Fig.3. The two figures are identified by Cassini's visual and infrared mapping spectrometer and inferred to be variable. The lobate, flow-like features in region 1 have been hypothesized to be due to cryovolcanic activity.

References:
STAR DUNES
Cecilia Leung

1. DUNE TYPES:
Figure 1. Types of sand dunes with prevailing wind direction

2. STAR DUNES:
aka: sand mountains, sand massifs, pyramidal dunes, stellate dunes.

Morphology:
- largest aeolian bedforms in many sand seas
- height may reach > 300m
- pyramidal shape
- 3-4 Sinuous arms radiating from central peak & multiple avalanche faces.
- most have dominant arm in preferred orientation.

Three Types of Star Dunes:
1. Simple: 3-4 equally developed arms & slipfaces
2. Compound: large primary arms & smaller subsidiary arms
3. Complex: combination dominant star dune & other dune types.

Fig. 1 Image from http://www.geo2all.com/

![Map of Major Areas of Star Dunes]

Figure 1 Major areas of star dunes: (1) Namib Sand Sea; (2) Erg Fachi-Bilma; (3) Grand Erg Oriental; (4) Rub al-Khali; (5) Badain Jaran Sand Sea; (6) Gran Desierto; (7) Mojave Desert.

![Map of Major Areas of Star Dunes on Earth]

Fig. 2 Major areas of star dunes on Earth

Table 1 Morphometry of star dunes in different sand seas

<table>
<thead>
<tr>
<th>Locality</th>
<th>Spacing (m)</th>
<th>Width (m)</th>
<th>Height (m)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean (range)</td>
<td>Mean (range)</td>
<td>Mean (range)</td>
</tr>
<tr>
<td>Namib¹</td>
<td>1230 (600-2600)</td>
<td>1000 (400-1000)</td>
<td>145 (80-350)</td>
</tr>
<tr>
<td>Niger²</td>
<td>1000 (150-3000)</td>
<td>610 (200-1200)</td>
<td></td>
</tr>
<tr>
<td>Grand Erg Oriental³</td>
<td>2070 (800-6700)</td>
<td>950 (400-3000)</td>
<td>117³</td>
</tr>
<tr>
<td>SE Rub al-Khali³</td>
<td>2060 (970-2600)</td>
<td>840 (500-1300)</td>
<td></td>
</tr>
<tr>
<td>Gran Desierto³ Clusters</td>
<td>2982 (1500-4000)</td>
<td>2002 (700-4000)</td>
<td></td>
</tr>
<tr>
<td>Dunes in clusters</td>
<td>312 (160-488)</td>
<td>163 (90-383)</td>
<td>89 (10-150)</td>
</tr>
<tr>
<td>Al-Shan³ (Badain Jaran Shamo)</td>
<td>137 (320-3200)</td>
<td>740 (400-1000)</td>
<td>200-330³</td>
</tr>
</tbody>
</table>

Sources: Lancaster (1983); Breed and Gath (1978); Wilson (1972); Hein (1980); Lancaster et al. (1987); Walker et al. (1987).
Environment:
- occur in areas representing depositional centers of many sand sea
- cover 5% of aeolian depositional surfaces
- area of sand sea covered by star dunes rarely more than 10%
- little migration

Formation:
- Lancaster 1989 Model
- may develop from complex linear dunes, and complex crescentic dunes.
- projection of transverse dunes into a complex, topographically influenced wind regime.

Fig. 3 Lancaster Model for star dune formation as dune migrate into multi-directional wind regimes

3. DUNES in DEATH VALLEY:

Five widely separated dune fields exist in Death Valley <1% area coverage

Mesquite Flat Dunes:
- Winds slowed by shape of the valley and towering Tucki Mountain.
- 3 types: barchans, linear, and star
  - complex wind pattern
- highest star dune only ~40m high

Figure 8  Surface wind patterns on a small star dune in the Gran Desierto, compiled from orientations of wind ripples: (A) northerly wind season; (B) westerly wind season; (C) southerly wind season.

Fig. 4 Example of surface wind patterns on a star dune in the Gran Desierto
4. STAR DUNES ON MARS:

Star dunes at 8.8°S, 270.9°W
- Locally confined, isolated occurrences, not part of a sand sea
- Field contains 11 star & incipient star dunes
- Nestled in valley formed by junction of crater rims
- Mars GCM suggest unimodal region winds
  • polymodal wind regime created by localized topography
  • progression from barchans → incipient stars → stars
- Recent Activity
  • Dark streaks indicate disruption of high-albedo materials
- Significance: insight into nature of martian wind conditions & sand supply.

Fig. 7 Martian star dunes. Dominant regional winds blow toward S-SW

References:
When fast moving water exits a canyon (so the flow is no longer constricted), the water slows down, loses energy, and deposits much of the sediment and debris it was carrying. The result is a fan-shaped deposit of material called an alluvial fan.

Major features of alluvial fans:

- **drainage basin** -- upland area where the water and sediment originate

- **feeder channel** -- highest order stream that feeds the fan (usually there's just one important feeder)

- **apex** -- the highest point on the fan where the feeder channel exits the upland area

- **incised channel** -- the downslope continuation of the feeder channel on the fan (it might remain as a single channel, but it could also divide into distributary channels)

- **intersection point** -- where the incised channel ends and merges with the fan slope.

- **active depositional lobe** -- past the intersection point, the flow expands laterally and you get active sediment deposition

- **headward-eroding gullies** -- erosion on the distal part of the fan (if it erodes far enough headward, it can create new intersection points, moving the active depositional lobe to a new area on the fan)

**alluvial fans in Death Valley**

A -- Trail Canyon
B -- Grotto Canyon
C -- Badwater fans

Figure 14.3 from Blair & McPherson 2009
Sedimentary processes on alluvial fans:

- **primary** -- transport of sediment from the drainage basin to the fan (rockfalls/avalanches, debris flows, floods, etc)
- **secondary** -- remobilization/modification of sediment previously deposited by primary processes (erosion/weathering, wind transport, faulting, plants, etc)

**alluvial fan dominated by water flows:**

![Diagram of an alluvial fan dominated by water flows]

- **fan apex**
- **incised channel**
- **fan intersection point**
- **drainage basin feeder channel**
- **Lower drainage basin**
- **Fault Scarp**
- **Talus cone**
- **Recently abandoned channel, surficial distributary channels & minor gullies**
- **Unmodified sheetflood deposits**
- **Distal-fan sandskirt**
- **Active depositional lobe**
- **Surficial braided-distributary channels**

**alluvial fan dominated by debris flows:**

![Diagram of an alluvial fan dominated by debris flows]

- **Lower drainage basin**
- **Fault Scarp**
- **Talus cone**
- **Recently abandoned fan lobe**
- **Debris-flow levees, lobes, & gullies**
- **Clast-poor debris flow**
- **Active depositional lobe**
- **Recent debris-flow levees & lobes**
- **'Older' debris-flow lobe**
- **Clast-poor debris flow**
- **Abandoned lobe: gully, winnowing of fines to produce gravel mantles**

Figure 14.10 from Blair & McPherson 2009
The radial profile of the fan depends on the sediment and its transport mechanism. The profile is generally either flat or slight concave, and there will be some size sorting along the fan (with sediment size decreasing along the radial profile).

**radial profile of an alluvial fan**  
(after figure 14.2 from Blair & McPherson 1994)

- steep debris cone
- clast-rich debris flows + bouldery sheetfloods 5-15°
- clast-poor debris flows + sandy sheetfloods 2-6°
- freefall debris 30-40°
- freefall + sediment/ gravity debris flows 10-30°

Some actual radial profiles (a) and cross profiles (b) of the fans in Death Valley:

![Figure 14.4 from Blair & McPherson 2009](image_url)
ideal conditions for creating alluvial fans:

- topography that causes a stream/channel to lose its lateral confinement and drain out onto a flat, low-lying area
- lots of sediment production in the drainage basin
- infrequent periods of high water discharge to carry the sediment out of the drainage basin

planetary connection:

Features very similar to desert alluvial fans have been seen on Mars, usually associated with craters. The crater walls provide the necessary topography for a fan to develop, and the impact itself could induce water/mud flows on the surface.

Titan may also have alluvial fans, as seen in this radar image and sketch (figure from Lorenz et al. 2006):

![Fig. 4. Northwestern rim of Mojave Crater at 7.6° N, 327° E (PSP_001481_1875). (A) Full browse image at greatly reduced resolution. Several locations of ponded and pitted material are labeled with "P"; boxed area shows the location of enlargement indicated in (B). (B) An example of where a large fan emanates from the ponded and pitted material to the northwest; boxed area shows enlargement to the full-resolution sample indicated in (C). (C) Braided and distributary channels and boulders up to ~1 m in diameter.](image)

Figure from McEwen et al. 2007

References:


Lorenz et al., Fluvial channels on Titan: Initial Cassini RADAR observations, Planetary and Space Science (2008)
Canyon Incision and Fluvial Erosion of Bedrock

- Colin Dundas

Overview
- Bedrock erosion is a fundamental control on the landscape.
- Feeds back into tectonics and uplift rates— isostasy.
- Conceptually (and perhaps simplistically), there is a transition from detachment-limited systems that erode bedrock and are limited by the ability of flows to detach rock, to transport-limited systems that are limited by the ability to move the supply of loose material.
- Some big-picture questions: How much erosion is performed by rare large events, as opposed to smaller, more frequent ones? How (by what processes) is bedrock eroded? How much erosion happens in events like the outflow channel floods on Mars? How much sediment do water flows transport?

Canyon Walls
- Physical and chemical weathering break down rock to sizes than can be moved by runoff and debris flows.

Fluvial Processes
- Several modes of sediment movement:
  - Bed load: rolling or bouncing along the channel floor.
  - Suspended load: held up in the flow by turbulent motions. (Somewhat equivalent to “wash load”, which undergoes minimal exchange with the bed).
  - Hyperconcentrated flows: grain settling hindered by grain contact and upward fluid flow driven by sinking grains. High flow density increases shear stress.
    - Hyperconcentrated flows transport much more sediment than others, but for coarse grains may require a massive supply of sediment.
    - A common assumption for calculating minimum outflow channel flood volumes is that the flows carried up to 40 vol% sediment, but 5% may be a more realistic estimate.
  - Debris flows: supported by sediment.
  - Abrasion: scouring by impact of sediment grains in transport.

Abrasion. (Whipple et al., 2000).
  - Tools effect: more sediment entrained in the flow enhances its ability to scour and abrade bedrock.
  - Cover effect: more material transported along the bed prevents impacting sediment from eroding the bedrock.
- Scouring by debris flows is to some extent an endmember of this process.
- Plucking: removal and entrainment of joint-bounded blocks.

Erosion by plucking. (Whipple et al., 2000).

- Cavitation: formation and collapse of bubbles when fluid pressure falls below the vapor pressure of air dissolved in the flow.

**Some Math**

Simplest of a large family of models: bedrock erosion rate is given by

$$\varepsilon = k\tau^a$$

where $\varepsilon$ is the erosion rate, $\tau$ is the shear stress at the base of the flow ($= \rho g D S$, where $\rho$ is the fluid density, $g$ is the acceleration due to gravity, $D$ is the flow depth and $S$ is the slope), and $k$ and $a$ are empirical constants. These laws are also sometimes written in terms of the stream power, which is just the product of the shear stress and the mean velocity, with basically the same form.

There are approximately as many versions of these laws as there are papers on the subject, possibly more. It’s not even clear that shear stress is the real controlling variable, as opposed to just a correlation, and in some cases none of them seem to work. For more detail, read the references. For even more detail, read the many other papers that cite or are cited by the references.

**References**


Phreatomagmatic Eruptions: Ubehebe Crater

By Amber Keske

What is a phreatomagmatic eruption?

In general, phreatomagmatic eruptions are the result of interaction between water and magma. The most common situation is when magma migrates too closely to a lake, the sea floor, or groundwater, whose heat vaporizes the water, resulting in an incredible upward force. This causes an eruption which expels a large quantity of steam, ash and rock. Such eruptions are typically on a much smaller scale than magmatic eruptions, producing pits known as maars.

Ubehebe Crater

Ubehebe crater (2.4 km wide and 180m deep) is the largest of a series of maars in a volcanic field in northern Death Valley which all formed at around the same time. The source magma for these eruptions was propagated through
a fault that lies along the western base of Tin Mountain, and upon coming into contact with subsurface water sources, caused the phreatomagmatic eruptions which formed the series of craters we see today. During the sizable eruption that created Ubehebe Crater, a pyroclastic flow known as a base surge, in which the unstable column of ash and rock near the ground began to collapse and surged outward at speed of up to 200 mph, blasted the Ubehebe-facing side of all objects in the area.

**Hazard?**

The age of Ubehebe Crater is disputed. It was long believed that the maars in this area were several thousand years old, from a time when Death Valley was wetter. However, recent rare isotopic evidence suggests that the complex may be around 800 years old, having occurred in a similar climate as we see now. This date is more consistent with the extent of erosion on the landforms, which seem to be relatively fresh. This evidence has raised concerns about whether the area might become volcanically active again. Since there are springs nearby (even around the crater), and not much water is required to incite a sizeable eruption, this is a very real possibility. However, hydrothermal and seismic activity would give good advance notice to any future eruptions.
Miscellaneous Topics about Playas
Shane Byrne, PTYS 594 – Spring 2012

Also known as Pans, Dry-lakes, alkali-flats or flats.

**Formation**
A playa contains interbedded lacustrine and evaporate deposits.

- Lacustrine deposits: Slits and Clays from pluvial periods
- Evaporates: Various salts from arid periods

Most southwestern playas were once lakes in the late-Pleistocene, fed by glacial meltwater. Things have been steadily drying out since then with a few interruptions. Lakes levels were oscillating with climate charges driven by Dansgaard–Oeschger oscillations, Heinrich Events, and Bond Cycles.

*Graph showing lake level variations over time*  
**Bacon et al. 2006**

Wetting and drying cycles in today’s climate give playas their characteristics:

1. Repeated wetting and drying transports fresh suspended material and solutes onto the playa. Within the playa the water collects in even the slightest low-areas.
2. Salts and suspended material are deposited when the water evaporates. Seepage instead of evaporation leads to clay pans rather than salt pans.

This process ensures that playas are remarkably flat, typically having only centimeters of relief over kilometers.
Evaporites are zoned with the least soluble salts coming out of solution first (near edges of a drying body of water).

- Outermost zone: Carbonates (CaCO₃ and MgCO₃)
- Middle zone: Sulfates (CaSO₄ and Na₂SO₄)
- Inner zone: Chlorides (NaCl, CaCl₂, KCl, MgCl₂)

**Post-Formation**

Playas are a source of dust-sized aerosols – Lack of surface roughness allows for very little aerodynamic drag and strong near surface winds. E.g. Owens Valley

Wetting and drying of clay minerals causes expansion and contraction. Contraction of clay from desiccation is analogous to contraction of lava from cooling (Goehring et al. 2009).

Faster desiccation gives you smaller polygons

Columns should expand in width with depth unless heat/moisture loss if forced to be constant.

Slow cooling/drying:
- Depth = polygon-scale
Fast cooling/drying:
- Depth = \sqrt{D \cdot t}
  (D=permeability/compliance)
Extraterrestrial Playas?
For all of Mars' ancient fluvial activity - Playas are remarkably absent!
Perhaps repeated wetting and drying did not occur.

Titan on the other hand certainly has Playas, as we've seen standing liquids come and go even over the course of the Cassini mission. There are plenty of fine-grained sediments to be mobilized on Titan. Atmospheric haze settles out at 0.1 μm/Titan-year.

Some closed basins in a region of Titan where lakes are common contain material bright at 5 μm. These basins have no outlet so evaporite deposits are a possibility.

Some organic compounds dissolve in methane. Evaporites could be benzene or CO₂.

References
1 Racetrack Playa Information

Figure 1: A trail behind a 15 cm rock. Figure from Lorenz et al. (2011).

- Size of playa: 4.5 km × 2 km
- Elevation: 1130 m. Varies by only a few centimeters from north to south.
- Dozens of rocks, often at the end of trails, are in the playa surface. The rock tracks were first observed in 1948.
- The tracks suggest the rocks moved across the playa when it was wet, but motion of the rocks has never been observed.
- Ice might facilitate rock movement which would require "unreasonably strong winds" if the rocks moved through wet mud or water in the absence of ice (Lorenz et al. 2011).

2 The Physics of Sliding Rocks

- The wind drag force, D, acting on a rock must exceed the force of friction (Figure 2).
- A floating ice sheet surrounding the rock could reduce the normal force and thus the friction. \((\text{normal force}) = (\text{weight}) - (\text{buoyancy})\). To make the rock float, it must be attached to ice \(\sim 20\) times its volume.
- Ice rafts a few centimeters thick and a few tens of centimeters wide can reduce the wind speed required to move a rock (Figure 3).
Figure 2: The forces on a rock and on a rock in an ice raft. Figure from Lorenz et al. (2011).

Figure 3: Wind speeds required to move a 20 cm rock (left) or a 10 cm rock (right) in water 10 cm deep (left) or 5 cm deep (right) as a function of ice raft diameter and thickness. Figure from Lorenz et al. (2011).

3 Other evidence for ice rafts:

- Tracks are parallel in some places suggesting two rocks were suspended in the same ice raft.

- Ice is known to transport rocks in other locations (glaciers, icebergs, etc.), and often forms around rocks in puddles or rivers.

- Observations have shown that Racetrack Playa freezes.

- Evidence for “plucking” - The depression at the start of some trails is deeper than the trail which might happen if a rock was first lifted vertically before moving horizontally (Figure 4).
Figure 4: The sitzmark of a rock. The trail is much shallower than the original depression. Figure from Lorenz et al. (2011).

- Sometimes the trail is not as wide as the rock itself which could happen if the rock were partially lifted out of the mud (see figure 9 in Lorenz et al. (2011)).

4 Requirements for Sliding Rocks

- A playa can only occur when evaporation rates exceed precipitation rates which typically occurs in mid-latitudes due to the atmosphere's Hadley circulation. They also must occur in local topographic minima to trap sediment.

- Because mid-latitudes are usually warm, the playa must be at a high elevation so it is cold enough for water to freeze.

- There must be a rock source, such as a cliff, adjacent to the playa.

5 Planetary Connection - Titan

- Ontario Lacus on Titan is also extremely flat (figures 5 and 6), experiences infrequent rainfall, and is in an environment where evaporation exceeds precipitation.

- Lower gravity and a thicker atmosphere might make rock transport more common on Titan than on Earth.

References


Figure 5: Figure from Lorenz et al. (2010).

Figure 6: Cassini Radar altimeter profile across Ontario Lacus (top). Transects from USGS topographic maps across Racetrack Playa (bottom). Figures from Lorenz et al. (2010).
**Ventifacts**

Sarah Morrison

**Definition:** rocks abraded by windblown particles such as sand

**Characteristics**[^1]

- Textures depend on rock shape, composition, and texture
- Hard, fine grained rocks become faceted
- Heterogeneous, coarse grained rocks become pitted or grooved
- Found in areas with sand, high winds, and sparse vegetation (desert, coastal, and periglacial environments)

**Formation**

- Windblown particles need enough kinetic energy to abrade rock
  - High winds, saltating sand particles[^1,2,3]

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Arguments in favor of sand as the principal abrasion agent in ventifact formation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dust</strong></td>
<td><strong>Sand</strong></td>
</tr>
<tr>
<td>Energy transfer to surface</td>
<td>Low energy. High velocity, but low mass. Particles are deflected around obstacle. Few impacts (10% as often as 100 ( \mu )m sand).</td>
</tr>
<tr>
<td>Abrasion profiles on vertical surfaces</td>
<td>Kinetic energy flux profile not consistent with abrasion seen on ventifacts or posts.</td>
</tr>
<tr>
<td>Erosional energy on level surfaces</td>
<td>Low energy near the surface and no abrasion.</td>
</tr>
<tr>
<td>Environment</td>
<td>Ventifacts not found in areas where dust alone is found. High energy. Lower velocity, but 1000× more mass. Particles hit windward face of obstacle. Many impacts. Secondary impacts possible due to rebound effects. Kinetic energy flux profile consistent with that observed on windward ventifact faces and posts. High energy near the surface from descending sand. Linear abrasion marks formed. Modern ventifacts found in sandy environments in arid, beach, and periglacial settings. Beach environments lack dust.</td>
</tr>
</tbody>
</table>

**Ventifacts as paleowind indicators**

- Direction of long axis of texture and facet dip = direction of strong winds

---

[^1]: 1. [Reference 1]
[^2]: 2. [Reference 2]
[^3]: 3. [Reference 3]
**Ventifacts on Mars**

- Lower atmospheric pressure, higher wind speed required to dislodge sand from surface (order of magnitude higher than for Earth)
  - Saltation on Mars is a higher kinetic energy process \(\rightarrow\) more effective at forming ventifacts\(^1\)
- Fairly common \(\rightarrow\) aeolian abrasion is a dominant erosion process
  - Found at Viking, Pathfinder, and Mars Exploration Rover sites
- Based on laboratory and Mars lander observations, abrasion is an ephemeral process for current Martian conditions\(^2\)
  - Integrated abrasion rate inferred from Pathfinder and Spirit \(\sim 10\)s of nm/yr
- Used to infer local prevailing wind direction

---

**Pits and flutes, Pathfinder site**

**Large, heavily fluted rock: Razor Road, Mojave Desert**
References
Salt Polygons
Meghan Cassidy

- drying and polygonal cracking of the playa surface as water evaporates.

**Two possible formation processes:**
- polygonal sheets expand laterally as salt crystallizes within them and the edges of the sheets override each other.
- salt crystallizes due to capillary action only along the polygonal cracks and the salt grows upward from the cracks in the form of inverted salt stalactites.

**Typical size**
Polygons: inches – feet across, ~ 6 inches deep
Salt crystals: 1 – 3 mm diameter
References:

1. Geology Underfoot in Death Valley (Sharp)
2. Death Valley (Hunt)
3. Dirty Money – Coming Home music video (Diddy)
Salt Weathering

Michelle Thompson

The process of salt weathering can have a significant influence on the geomorphology of surface material, particularly along coastline and desert landscapes on Earth. While most easily observed on Earth, this destructive process has been identified on the surface of Mars using images taken from the robotic landers (Figure 1). While salt weathering produces a characteristic effect on the rock structure, the mechanism that drives this process can vary significantly depending on the environment. The physical and chemical effects of salt-induced weathering will be discussed below.

What is Salt Weathering?

The process of weathering is the breakdown of rocks and minerals through interaction with some external force (e.g., water, the atmosphere, biological agents). Weathering is completed in situ (not to be confused with erosion which requires the transport of material). Weathering processes can be divided into two distinct subgroups:

1) Chemical: disintegration of rock material through alteration of the chemical composition of constituents.
2) Mechanical: break-down of the rock and its minerals to smaller grain size without chemical alteration.

Both of these processes are observed on Earth and other planetary surfaces, including Mars. Salt weathering is primarily a mechanical weathering process that is caused by the expansion of salt crystals in the pore spaces and cracks in an existing rock. This expansion can be caused by three independent mechanisms:

1) Growth of salt crystals in confined spaces through evaporation of saline solutions
2) The hydration of salt crystals causing a change in volume
3) Thermal expansion of salt crystals as a consequence of (day-time) heating (thermal expansion coefficient of salt must exceed that of the rock)

In order to generate salt weathering, the rocks typically come into contact with a salty solution. This fluid is drawn into the rock pore spaces and cracks through capillary action and is evaporated, depositing salt crystals. In arid terrestrial environments such as Death Valley, both ground and surface water undergoes immense evaporation, concentrating salts in solution to create water with a very high salinity. The interaction of this water with rock material causes the mechanism of salt weathering.

Figure 1: Salt weathering effects on a) rocks in Argentina; b) the surface of Mars (image by Spirit rover) (Jagoutz 2006).
It is important to note that ‘salt’ refers not exclusively to common rock or table salt (NaCl) but may be several distinct salt-minerals (e.g., sodium sulfate Na₂SO₄, magnesium sulfate Mg₅SO₄, calcium chloride CaCl₂, etc.).

Salt Weathering in Death Valley:

Death Valley exhibits some of the best evidence for salt weathering on Earth. The predominant salt-mineral that contributes to weathering in this region is halite (rock/table salt NaCl). It is particularly noticeable in regions where the alluvial fans meet the salt pans on the floor of the valley.

It is true in all regions, and Death Valley is no exception, that particular rock types are more susceptible to salt weathering (and all weathering types) than others (Figure 2). Weathering effects are most pronounced in rocks with high porosity (e.g., coarse grained or sedimentary units) or those with existing planes of weakness (e.g., foliation planes in gneisses or fracture planes in stressed rocks). Rocks and minerals that do not exhibit cracking or structural heterogeneity are least susceptible to this force of weathering.

The rate at which salt weathering alters the surface can be extremely rapid. It is estimated that boulders in Death Valley up to a meter in size have been reduced to fragments <10 cm in less than 10,000 years.

Salt Weathering in the Solar System:

Evidence of salt weathering has been discovered on the surface of Mars through analysis of images taken by the planetary surface rovers (Figure 3). This is an important identification, as salt weathering typically indicates the presence of a saline fluid, suggesting that the region where this phenomenon has been identified was exposed to liquid (likely water) at some point in its history. In addition, identifying and characterizing these features enables us to constrain the rate of weathering on planetary surfaces.

![Figure 3: Image of a rock a) thought to have undergone salt weathering; b) the reconstruction of its original configuration (Spirit Rover) (Jagoutz 2006).](image)

References:


The Waxing and Waning of the Ancient Lake Manly
Corwin Atwood-Stone

Ancient Lake Manly
-Lake Manly was a pluvial, endorheic lake which occupied the
Death Valley during several portions of the Pleistocene
-The most recent major lake was present approximately
20,000 - 10,000 years ago
-This lake was 80-90 miles long, 6-11 miles wide and up to
600 feet deep in some areas
-This lake was fed primarily by the Amargosa River and had
no outflows, being draining primarily by evaporation

Recent Shadows of Lake Manly
-During a period about 2,000 years ago a smaller lake
approximately 30 feet deep formed during the brief wet
period of the Holocene
-In modern times occasional severe storms can briefly flood
the valley to form very small lakes
-Most notably in 2005 a lake formed covering over 100 square
miles to a depth of up to 2 feet
-These lakes are highly ephemeral as
the area’s 150 inch annual evaporation
rate dominates over the 1.9 inches of
average rainfall
-Some water remains at the surface
year round at Badwater, which at
282 feet below sea level is the only
surface expression of the major aquifer
which lies under Death Valley
-Despite being extremely salty this small
pool supports an interesting variety of
life including pickleweed, the badwater
snail, and the Death Valley pupfish

Naming of Lake Manly
-Lake Manly is named for Pioneer
William L. Manly who in 1849 with
friend John Rogers walked 250 miles
out of Death Valley to a ranch near
LA to scout a route for the families
they were traveling with, and then
with $30 worth of supplies walked
back to their fellow travelers to
lead them to safety
-These were the first pioneers to
cross Death Valley
Evidence of Lake Manly
-The first evidence of Lake Manly was discovered by Levi Noble in 1924.
-He discovered wave terraces on a basalt hill that is now known as Shoreline Butte.
-Other sets of terraces were later found at other areas along the perimeter of the lake.
-The elevations of the terraces in each set match each other fairly well, indicating that they were formed during periods of stable lake level.
-On some of these terraces, and in other locations, Tufa is found to have formed on pebbles, and in 2-3 inch thick deposits on the bottoms of talus blocks.
-In one area in the northern portion of the lake there are calcareous white deposits of powdery chalk and dense limestone with algaloid structures. These deposits are of fairly definative lacustrine origin.

More Evidence and Earlier Lakes
-The surface of a large area of Death Valley is a thick salt layer which is believed to be an evaporite deposit from the desiccation of Lake Manly.
-Wells drilled through this surface in 1914 by the USGS found a thick layer of dark salty clay, formed while the lake was growing and stable.
-These wells each were drilled down until they reached the aquifer, the deepest being 104 ft.
-The entire stratigraphic sequence seen in these wells is alternation of salt and clay layers indicating the existence of a whole series of Lake Manlys.
-The sequence observed in these wells indicates the existence of three major lakes and a number of more transient ones.
Shoreline Features
Donna Viola

- Death Valley was once contained pluvial lakes (~186,000-128,000 years ago).
- **pluvial lake** — inland body of water that forms during periods of glaciation, due to precipitation and glacial melt
- The largest of these pluvial lakes was Lake Manly (Figure 1), which may have been as much as 160km long and 180m deep.
- Lake Manly dried up about 10,000 years ago, and has since only been subject to occasional flooding.

Figure 1: Map of pluvial lakes in Death Valley during its last maximum, 22,000 years ago. USGS.

Shoreline Butte:

- was an island in Lake Manly during the Pleistocene
- contains preserved shorelines (Figure), also known as strandlines
- Each level represents a different depth of Lake Manly at a different point in time.

Figure 2: Shoreline butte; erosional platforms can be observed in the left image and are labeled on the right.

Figure 3: Example of lacustrine terrace formation. Marx et al, 2009
**Lacustrine terrace/strandline formation:**
Terraces and strandlines can form whenever the water level in a lake is stable for a long enough period of time for incision to occur. As waves batter the shoreline, they erode a new terrace. When the water level drops, a new level can be formed by incision. Figure 3 depicts the formation of a lacustrine terrace due to a drop in water level. Figure 4 shows an example of the change in altitude of terraced levels for a lake in Spain.

![Time sequence for a terrace system in NE Spain. Prieto, 1995.](image)

**Strandlines on Mars?**

In 2009, the first strandlines on Mars were discovered using HiRISE imagery from Shalbatana Vallis. These are thought to be the result of a Hesperian-era paleolake. Figure 5 shows MOLA and visible imagery of the paleolake and the strandlines, as well as the cross section of the lake based on elevation data.

![MOLA data showing the depression from a paleolake b) HiRISE image showing strandlines c) Lake cross-section based on elevation data. Di Achille et al, 2009.](image)

References:
http://en.wikipedia.org/wiki/Pluvial_lake
Cinder Cones in the Cima Volcanic Field

Youngmin JeongAhn

More than 30 cinder cones are located in the Cima volcanic field, Mohave Desert, with basaltic lava flows. A Cinder cone is a common type of simple volcano and characterized by steep slope, conical shape and smaller size than composite volcanoes. Usually they are composed of ejected basaltic tephra and formed by strombolian eruption. Cinder cones in the Cima volcanic field were erupted during the Pleistocene (2588-11.7 kyrs BP) while surrounding lava flows are dated up to 7.6 million year ago, during the Neogene.

The youngest cinder cone (A in the attached map) was formed 15 thousand years ago and it is closely located to our campsite. The oldest cinder cone (CC) was erupted 1.1 million years ago and some of the cones have evidence that they are erupted from the same vents. K-Ar and ¹⁴C analyses are used to determining cone ages and paleomagnetic polarity is used to support the dating.

Cone heights range from 50 to 155m (90m for A) and mean width range from 400 to 915m (540m for A). Crater depth and width are 45m and 330m for younger cones, respectively. Erosion with time reduces cone height and slope. Cone-height/cone-width ratio (0.17 - 0.14), Crater-width/cone-width ratio (0.48 - 0.21), and tangent value of mean maximum slope (0.575 - 0.414) decrease as increasing the age.

Cone age also affects drainage morphology. Debris-flow is dominant for the early evolution of degradation and piping flow is also important to upslope migration of collapse and gully elongation on younger cones.

<table>
<thead>
<tr>
<th>Age</th>
<th>Drainage morphology</th>
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</thead>
<tbody>
<tr>
<td>Youngest (A)</td>
<td>Unevenly spaced rills and gullies on the outer slopes</td>
</tr>
<tr>
<td>0.15 – 0.25 myr</td>
<td>A lot of regularly distributed gullies on lower and middle slopes</td>
</tr>
<tr>
<td>0.30 – 0.35 myr</td>
<td>Parasol-like patterns of straight gullies from the toe to the crest</td>
</tr>
<tr>
<td>0.59 - older</td>
<td>Larger, widely spaced, intersect each other</td>
</tr>
</tbody>
</table>

Broz & Hauber(2011) interpreted some volcanic landforms of Tharsis on Mars as cinder cones (images below). Their basal diameter is 2.6 times larger than that of cinder cones on the Earth. Crater-width/cone-width ratio (0.277) is close to that of terrestrial cinder cones (0.288).
Figure 2. Generalized geologic map of the southern part of the Cima volcanic field showing the locations of cones discussed in the text.
Main Reference

Minor Reference

Color maps from Google Earth
Lava flow age dating, Cima volcanic field
Melissa Dykhuis

How old is a lava flow?
- **Who cares?**
  - Planetary scientists. Basaltic lava flows are common on planetary surfaces (e.g. Mars, Venus, the Moon, asteroids?), and we want good ways to find the ages of planetary surfaces (Arvidson et al. 1993).
  - Volcanologists. They have to study and predict volcanic lava flow.
- **How do we date lava flows on Earth?** (where we are lucky enough to be able to pick up [cooled] lava flow rocks)
  - Radiometric dating. (K-Ar, works well for basaltic lava flows like Cima, Dohrenwend et al. 1984)
  - Desert varnish! (Liu 2003)
  - Or, if you're brave, you could watch the lava flow happen. Historical accounts of volcanic activity (e.g. the Mt. Etna region c. 1300 to present, Mazzarini et al. 2006) can be used to calibrate age dating techniques.
- **How could we date lava flows on other planetary surfaces?** (where we mostly look, but don’t touch)
  - Observations of surface roughness. Due to eolian processes, lava flows can become smoother with time. If rocks stick out, they get weathered down (mass-wasting, communism); if rocks have holes, wind fills them with dirt.
Caveat: A lot of planetary bodies don’t have water or wind or tourists to weather things down. So age-roughness calibrations on other planetary surfaces usually necessitate guesses about the types and extents of degradation processes on those bodies.

That being said, Cima volcanic field provides an excellent Earth analog for extraterrestrial lava flow age dating.
- Why Cima is great
  - Arid region
  - Lava flow nursery: flows from 0.016 to 7.6 Ma
  - Well studied over the past century, first publication on the region was Darton et al. 1916.
  - Independent ages on several different lava flows from $^3$He, $^{36}$Cl, K-Ar, $^{40}$Ar/$^{39}$Ar dating methods, and desert varnish microstratigraphy -- see “Table 3” below for comparison.
  [Worth noting: the radiometric dating techniques often have to assume an erosion rate for the lava flows. Phillips 2003 assumed 1 mm/yr for the Cima volcanic field.]

<table>
<thead>
<tr>
<th>Table 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison of age estimates for Mojave Desert basalt flows</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow</th>
<th>$^{36}$Cl (this study)</th>
<th>Varnish microstratigraphy</th>
<th>$^{3}$He</th>
<th>$^{40}$Ar/$^{39}$Ar</th>
<th>K–Ar</th>
<th>Geomorphic comparison and other methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pisgah</td>
<td>22.5 ± 1.3</td>
<td>30–24</td>
<td></td>
<td></td>
<td></td>
<td>&lt;2 (Kilbourne and Anderson, 1981)</td>
</tr>
<tr>
<td>Amboy</td>
<td>79 ± 5</td>
<td>85–74</td>
<td></td>
<td></td>
<td></td>
<td>&lt;1 (Darton et al., 1916), &lt;6 (Parker, 1963), &lt;2 (Kilbourne and Anderson, 1981)</td>
</tr>
<tr>
<td>Cima “I”</td>
<td>27 ± 3</td>
<td>39</td>
<td>37 ± 6, 31 ± 7</td>
<td>140 ± 20</td>
<td>(Dohrenwend et al., 1984), 110 ± 5, (Turrin and Champion, 1991)</td>
<td></td>
</tr>
<tr>
<td>Cima “uk”</td>
<td>46 ± 2</td>
<td>60–46</td>
<td>19 ± 11, 13 ± 3</td>
<td>119 ± 14</td>
<td>~ 300 (Turrin, 1989$^b$)</td>
<td></td>
</tr>
<tr>
<td>Cima “A”</td>
<td>21 ± 6, 11.5 ± 1.5</td>
<td>24–16.5</td>
<td></td>
<td></td>
<td></td>
<td>29–16 [paleomagnetism] (Champion, 1990$^b$), 9 ± 0.8 [thermoluminescence] (Forman, 1992$^b$), &lt;0.5 [geomorphic] (Katz and Boettcher, 1990)</td>
</tr>
</tbody>
</table>

All ages are in ka.

$^a$ Quoted in Wells et al., 1994.
$^b$ Quoted in Wells et al., 1990.

Table from Phillips 2003

Observations of Cima lava flow roughness

Summary of Cima work: Roughness dating is hard to do. Several scientists have tried, for the Cima region, with limited success and lots of scatter in their data. This could be in part due to the scatter in ages determined via several different methods, see the above chart.

Farr 1992, for example, used stereophotography to find that the surfaces initially become smoother with age under eolian weathering processes, till about 0.5-0.8 My have gone by, after which the trend reverses due to fluvial erosion/incision. The next few plots show the data from this paper.
Fig. 5. Power spectra of dated flow surfaces, showing evolution with age. Power decreases over all scales between 0.016 and 0.56 m.y. Linear fits (not shown) show a slight change in slope, as well. Flows older than 0.56 m.y. show a reversal in the trend toward decreasing offset with age. Most of the difference is concentrated in the middle wavenumbers (3–70 m$^{-1}$, or 2 m to 9 cm). Note also that the 0.99-m.y. spectrum can be better fit by three line segments.

Fig. 6. Results of linear fits to power spectra of dated flow surfaces. Power spectrum offset decreases with age until 0.85 m.y., when it returns to values similar to younger flows. Power spectrum slope at first steepens (more negative), then flattens from 0.14 to 0.85 m.y., and finally returns to steep values of young flows.
References


Desert Pavement by Gabriel Muro

Desert pavements, consisting of a one- to two-particle thick layer of closely packed, interlocking angular or rounded rock fragments of pebble and cobble size, are one of the more prominent landforms of the natural arid regions across the world.

The origin and evolution of stone pavements on the basalt flows are directly linked to two fundamental processes: (1) deposition and pedogenic alteration of the eolian mantle and (2) mechanical weathering to form the rubble zone. The source of the clasts in the pavement is mechanically weathered basaltic bedrock derived from topographic highs. Salt-rich eolian fines accumulate in fractures of the basalt, and wetting and drying of the fines result in volumetric changes related to crystal growth or shrinking and swelling of clay. This volumetric change enhances fracturing and displaces the basaltic clasts vertically and laterally. As displacement occurs, additional eolian fines and salts are deposited between the clasts, further enhancing separation of clasts from underlying bedrock. Mechanical weathering of topographic highs also results in the development of colluvial wedges of rubble and the concomitant infilling of topographic depressions with the colluvial material. These clasts move laterally by colluvial and alluvial processes into the topographic lows in which abundant silt has accumulated, and they form a surface layer of stones.

On progressively older flows, the extent of bedrock highs decreases as the eolian mantle and stone pavement filling the lows and coalesce; thus, the source area for basalt clasts is significantly reduced on flows older than 0.4 Ma. Pavements on flows younger than 0.4 Ma indicate fewer differences in the residence time of clasts in the pavement. This is supported by the data on the reddening clast undersides: only 10-20% of clast undersides in pavements on flow younger than 0.4 Ma have weakly reddened, oxidized coatings, whereas clasts undersides on flows older than 0.4 Ma are all reddened. This suggested that no new clasts are added to pavements once the bedrock topographic highs are reduced by erosion and buried by eolian sediments, and once stones are added to the pavements, they are typically maintained at the surface by processes that inhibit burial.

Age data for the flows and soil-stratigraphy indicate that the most recent period of relatively high eolian influx rates occurred during the latest Pleistocene to early Holocene. The apparent timing of the most recent eolian event and the accumulation of large quantities of carbonates and soluble salts in these soils strongly suggest that alkaline playas, formed after the disappearance of late Pleistocene pluvial lakes in the Mojave Desert, are a major source of these eolian materials.
Wherever found, desert pavement plays a fundamental role in the long-term evolution of the land surfaces as it mantles. Surface clasts protect underlying sediments and soil from removal by wind and water and provide a substrate for the capture of eolian sand, silt, clay and salts. Infiltration is dramatically reduced and precipitation is redirected to nearby bare ground areas where vegetation clusters.

In the eastern Mojave Desert, the landscape is spatially heterogeneous with wide stretches of barren desert pavement surrounding meter-wide regions of bare ground where shrubs cluster. These two broad landscapes can be further divided into six visually distinct, readily mapped surface mosaics. Three distinct surface mosaics (DP1, DP2, DP3) represent desert pavement regions where surface clast coverage is >65%, and the other three (BG1, BG2, BG3) represent bare ground regions where surface clast coverage is <65%.

The depth of soil water movement and solute transport is strongly tied to surface clast differences across the landscape. Measured electricity conductivity values at all soil depths except 5-10 cm correlate to percent clast cover, indicating that soluble salts are carried by the wind from nearby playas and deposited on the surface as dust, concentrating at shallower depths as percent clast cover increases. The three DP surfaces have shallow leaching regimes with soluble salts accumulated near the land surface. In contrast, the BG surfaces have deep leaching regimes that prevent the accumulation of soluble salts within the top 50-cm. Deeper leaching regimes of the three BG surfaces suggest where infiltration of rainwater is unimpeded. In contrast, surface run-off predominates on the DP surfaces.

Since available water is the primary limit on desert plant growth, the relationship with run-off and rainwater infiltration reflects the precise control of soil moisture by closely juxtaposed differences in the clast cover. The phenomenon of percent shrub cover strongly correlating to percent clast cover has been observed throughout North American deserts of different aged land surfaces. This suggests that the physical character of the top few centimeters of arid land surfaces is core in determining the spatial distribution of water across arid landscapes, independent of landform, soil, or age.
Desert pavements on surfaces are usually covered by rock varnish, a coating built up over many decades by windblown cay particles and the bacteria that live on them. Since varnish has been found on World War II-era fuel cans left in the desert, we know that it can form fairly fast, geologically speaking. Changes in the chemical composition of varnish and the presence of organic carbon have proved to be useful for estimating the age of the underlying material, but age estimates are not perfect since varnish is not uniform across every rock. This is likely due to floodwaters disturbing the surface every few centuries.

According to a recent NASA press release: when Chris McKay examined the carbonate rocks from collected from the Mojave Desert, he found that it became evident that an iron oxide skin may be hindering the search for clues to the Red Planet’s hydrological history. This is because varnish both altered and partially masked the spectral signature of the carbonates. McKay also found dehydration-resistant blue-green algae under the rock varnish. Scientists believe the varnish may have extended temporarily the time that Mars was habitable, as the planet’s surface slowly dried up.

Cima Dome is a place where lava flows of recent age, geologically speaking, are partly covered by younger soil layers that have desert pavement on top of them, made of rubble from the same lava. Obviously, the soil has been built up, not blown away. By entrapping fine-grained material, this rocky surface continues to be pushed up as windblown dust continues to make a thick layer over millennia. Mars’ surface on the windy floor of Gusev crater appears to be a planetary analog to desert pavement. For a future Mars-geologists, the dust deposition beneath some desert pavements may have preserved a record of ancient climate, just as on the Earth’s seafloor and ice caps.

McFadden, L., Wells, S., Dohrenwend, J. “Influences of Quaternary climatic changes on processes of soil development on the desert loess deposits of the Cima volcanic field, California” Catena 13, 1986: 361-389
Death Valley Bingo

Fill in your Bingo card from the word bank below. When you hear a word over the CB or in conversation in the car, cross out that square. See who can get five in a row first!

Word Bank

gas basalt flow California limestone relief Arizona valley geomorphology deposition magma tectonics uplift stratigraphy bedding weathering stop drift granite fault break volcanic sedimentary water crust igneous mineral clay basement graben gravity desert stress radiative thermal viscosity variation
How Much Time Do You Waste at the Quote Board?
Across
2. “My ________ is perfectly adequate.”
3. “I’m surprised you didn’t ________ the model harder.”
5. “I’ve got _________, I don’t need time.”
6. “I like to do the _________ ones.”
8. a rare breed of _________ sasquatch
10. “You shall not _________.”
11. _________ wave
12. “________ to drunk!”
13. “Big _________ are wimpy.”
16. “I’m too hot for _________.”

Down
1. “It’s been the _________ for a while now.”
4. “The Cure is like the _________ of the music industry.”
7. “I’m not happy unless my _________ are warm.”
8. “Why does it always smell like _________ in here?”
9. “Are you celebrating _________’s Law this afternoon?”
10. ”A sharp _________ is its own reward.”
14. “You have no idea how great my _________ is.”
15. ”He’s _________, Rob. He’s _________er than you.”

18 of 20 words were placed into the puzzle.
| Name ___________________________ | K Miller |

**M A S H - O**

Number of lines ______

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<thead>
<tr>
<th>Husband/wife</th>
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<th>City you live in</th>
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</table>
Aa: A blocky and fragmented form of lava occurring in flows with fissured and angular surfaces.
Alkaline metal: A strongly basic metal like potassium or sodium.
Alluvial fan: A low, cone-shaped deposit of terrestrial sediment formed where a stream undergoes an abrupt reduction of slope.
Alluvium: Unconsolidated terrestrial sediment composed of sorted or unsorted sand, gravel, and clay that has been deposited by water.
Angle of repose: The steepest slope angle in which particular sediment will lie without cascading down.
Aquifer: A permeable formation that stores and transmits groundwater in sufficient quantity to supply wells.
Arroyo: A steep-sided and flat-bottomed gully in an arid region that is occupied by a stream only intermittently, after rains.
Artesian well: A well that reaches an aquifer containing water under pressure. Thus water in the well rises above the surrounding water table.
Barchan: A crescent-shaped sand dune moving across a clean surface with its convex face upwind and its concave slip face downwind.
Basalt: A fine-grained, dark, mafic igneous rock composed largely of plagioclase feldspar and pyroxene.
Basement: The oldest rocks recognized in a given area, a complex of metamorphic and igneous rocks that underlies all the sedimentary formations.
Basic rock: Any igneous rock containing mafic minerals rich in iron and magnetism, but containing no quartz and little sodium rich plagioclase feldspar.
Basin: In tectonics, a circular, syncline-like depression of strata. In sedimentology, the site of accumulation of a large thickness of sediments.
Batholith: A great irregular mass of coarse-grained igneous rock which has either intruded the country rock or been derived from it through metamorphism.
Bathymetry: The study and mapping of sea-floor topography.
Bedding: A characteristic of sedimentary rocks in which parallel planar surfaces separating different grain sizes or compositions indicate successive depositional surfaces that existed at the time of sedimentation.
Bolson: In arid regions, a basin filled with alluvium and intermittent playa lakes and having no outlet.
Butte: A steep-sided and flat-topped hill formed by erosion of flat lying strata where remnants of a resistant layer protect the softer rocks underneath.
Caldera: A large, circular depression in a volcanic terrain, typically originating in collapse, explosion, or erosion.
Carbonate rock: A rock composed of carbonate minerals, especially limestone and dolomite.
Cataclastic rock: A breccia of powdered rock formed by crushing and shearing during tectonic movements.
Chemical weathering: The total set of all chemical reactions that act on rock exposed to water and atmosphere and so change it minerals to stable forms.
Chert: A sedimentary form of amorphous or extremely fine-grained silica, partially hydrous, found in concretions and beds.
Cinder cone: A steep, conical hill built up about a volcanic vent and composed of coarse pyroclastics expelled from the vent by escaping gases.
Clastic rock: A sedimentary rock formed from mineral particles (clasts) that were mechanically transported.
Clay: Any of a number of hydrous aluminosilicate minerals formed by weathering and hydration of other silicates.
Composite cone: The volcanic cone of a stratovolcano, composed of both cinders and lava flows.
Deflation: The removal of clay and dust from dry soil by strong winds.
Delta: A body of sediment deposited in an ocean or lake at the mouth of a stream.
Deposition: A general term for the accumulation of sediments by either physical or chemical sedimentation.
Deposition remnant magnetization: Magnetization created in sedimentary rocks by rotation of magnetic crystals into line with the ambient field during settling.
Desert pavement: A deposit produced by continued deflation, which removes the fine grains of a soil and leaves a surface covered with closely packed cobbles.
Detrital sediment: Sediment deposited by a physical process.
Diagenesis: The physical and chemical changes undergone by a sediment during lithification and compaction, excluding erosion and metamorphism.
Diatreme: A volcanic vent filled with breccia by the explosive escape of gases.
Dip: The angle by which a stratum or other planar feature deviates from the horizontal. The angle is measured in a plane perpendicular to the strike.
Drainage basin: A region of land surrounded by divides and crossed by streams that eventually converge to one river or lake.
Drift (glacial): A collective term for all the rock, sand, and clay that is transported and deposited by a glacier either as till or as outwash.
Dune: An elongated mound of sand formed by wind or water.
Eolian: Pertaining to or deposited by wind.
Epicenter: The point on the Earth's surface directly above the focus or hypocenter of an earthquake.
Erosion: The set of all processes by which soil and rock are loosened and moved downhill or downwind.
Evaporite: A chemical sedimentary rock consisting of minerals precipitated by evaporating waters, especially salt and gypsum.
Exfoliation: A physical weathering process in which sheets of rock are fractured and detached from an outcrop.
Fault: A planar or gently curved fracture in the Earth's crust across which there has been relative displacement.
Fault plane: The plane that best approximates the fracture surface of a fault.
Felsic: An adjective used to describe a light-colored igneous rock poor in iron and magnesium content, abundant in feldspars and quartz.
Fissure: An extensive crack, break, or fracture in the rocks.
Flood basalt: A plateau basalt extending many kilometers in flat, layered flows originating in fissure eruptions.
Flow cleavage: In a metamorphic rock, the parallel arrangement of all planar or linear crystals as a result of rock flowage during metamorphism.
Fluid inclusion: A small body of fluid that is entrapped in a crystal and has the same composition as the fluid from which the crystal formed.
Focus (earthquake): The point at which the rupture occurs; synonymous with hypocenter.
Fold: A planar feature, such as a bedding plane, that has been strongly warped, presumably by deformation.
Foliation: Any planar set of minerals or banding of mineral concentrations including cleavage, found in a metamorphic rock.
Forset bed: One of the inclined beds found in crossbedding; also an inclined bed deposited on the outer front of a delta.
Fricion breccia: A breccia formed in a fault zone or volcanic pipe by the relative motion of two rock bodies.
Fumarole: A small vent in the ground from which volcanic gases and heated groundwater emerge, but not lava.
Geochronology: The science of absolute dating and relative dating of geologic formations and events, primarily through the measurement of daughter elements produced by radioactive decay in minerals.
Geomorphology: The science of surface landforms and their interpretation on the basis of geology and climate.
Geosyncline: A major downwarp in the Earth's crust, usually more than 1000 kilometers in length, in which sediments accumulate to thicknesses of many kilometers. The sediments may eventually be deformed and metamorphosed during a mountain-building episode.
Geotherm: A curving surface within Earth along which the temperature is constant.
Geyser: A hot spring that throws hot water and steam into the air. The heat is thought to result from the contact of groundwater with magma bodies.
Glacial rebound: Epeirogenic uplift of crust that takes place after the retreat of a continental glacier in response to earlier subsidence under the weight of ice.
Glacial striations: Scratches left on bedrock and boulders by overriding ice, and showing the direction of motion.
Glacial valley: A valley occupied or formerly occupied by a glacier, typically with a U-shaped profile.

Glacier: A mass of ice and surficial snow that persists throughout the year and flows downhill under its own weight, of sizes 100 m – 10000 km.

Glass: A rock formed when magma is too rapidly cooled (quenched) to allow crystal growth.

Graben: A downthrown block between two normal faults of parallel strike but converging dips; hence a tensional feature. See also horst.

Graded bedding: A bed in which the coarsest particles are concentrated at the bottom and grade gradually upward into fine silt.

Granite: A coarse-grained, intrusive igneous rock composed of quartz, orthoclase feldspar, sodic plagioclase feldspar, and micas.

Gravity anomaly: The value of gravity left after subtracting the reference value based on latitude, and possibly the free-air and Bouguer corrections.

Gravity survey: The measurement of gravity at regularly spaced grid points with repetitions to control instrument drift.

Groundwater: The mass of water in the ground below the phreatic zone occupying the total pore space in the rock.

Horst: An elongate, elevated block of crust forming a ridge or plateau, typically bounded by parallel, outward-dipping normal faults.

Hydration: A chemical reaction, usually in weathering, which adds water or OH to a mineral structure.

Hydraulic conductivity: A measure of the permeability of a rock or soil: the volume of flow through a unit surface in unit time with unit hydraulic pressure difference as the driving force.

Hydrologic cycle: The cyclical movement of water from the ocean to the atmosphere, through rain to the surface, through runoff and groundwater to streams, and back to the sea.

Hydrology: The science of that part of the hydrologic cycle between rain and return to the sea; the study of water on and within the land.

Hydrothermal activity: Any process involving high-temperature groundwaters, especially the alteration and emplacement of minerals and the formation of hot springs and geysers.

Hydrothermal vein: A cluster of minerals precipitated by hydrothermal activity in a rock cavity.

Igneous rock: A rock formed by congealing rapidly or slowly from a molten state.

Inclination: The angle between a line in the Earth's magnetic field and the horizontal plane; also a synonym for dip.

Infiltration: The movement of groundwater or hydrothermal water into rock or soil through joints and pores.

Intrusion: An igneous rock body that has forced its way in a molten state into surrounding country rock.

Intrusive rock: Igneous rock that is interpreted as a former intrusion from its cross-cutting contacts, chilled margins, or other field relations.

Isograd: A linear or curved surface connecting rocks that have undergone an equivalent degree of metamorphism.

Isoptasia: The mechanism whereby areas of the crust rise or subside until the mass of their topography is buoyantly supported or compensated by the thickness of crust below, which "floats" on the denser mantle. The theory that continents and mountains are supported by low-density crustal "roots."

Isotope: One of several forms of one element, all having the same number of protons in the nucleus but differing in number of neutrons and atomic weight.

Joint: A large and relatively planar fracture in a rock across which there is no relative displacement of the two sides.

Laccolith: A sill-like igneous intrusion that forces apart two strata and forms a round, lens-shaped body many times wider than it is thick.

Lahar: A mudflow of unconsolidated volcanic ash, dust, breccia, and boulders mixed with rain or the water of a lake displaced by a lava flow.

Laminar flow: A flow regime in which particle paths are straight or gently curved and parallel.

Lapilli: A fragment of volcanic rock formed when magma is ejected into the air by exploding gases.

Lava: Magma or molten rock that has reached the surface.

Lava tube: A sinuous, hollow tunnel formed when the outside of a lava flow cools and solidifies and the molten material passing through it is drained away.

Leaching: The removal of elements from a soil by dissolution in water moving downward in the ground.

Left-lateral fault: A strike-slip fault on which the displacement of the far block is to the left when viewed from either side.

Levee: A low ridge along a stream bank, formed by deposits left when floodwater decelerates on leaving the channel.

Limb (fold): The relatively planar part of a fold or of two adjacent folds (for example, the steeply dipping part of a stratum between an anticline and syncline).

Limestone: A sedimentary rock composed principally of calcium carbonate (CaCO2), usually as the mineral calcite.

Lithification: The processes that convert a sediment into a sedimentary rock.

Lithology: The systematic description of rocks, in terms of mineral composition and texture.

Lithosphere: The outer, rigid shell of the Earth, situated above the asthenosphere and containing the crust, continents, and plates.

Lode: An unusually large vein or set of veins containing ore minerals.

Longitudinal dune: A long dune parallel to the direction of the prevailing wind.

Lopolith: A large laccolith that is bowl-shaped and depressed in the center, possibly by subsidence of an emptied magma chamber beneath the intrusion.

Maar volcano: A volcanic crater without a cone, believed to have been formed by an explosive eruption of trapped gases.

Mafic mineral: A dark-colored mineral rich in iron and magnesium, especially a pyroxene, amphibole, or olivine.

Magma: Molten rock material that forms igneous rocks upon cooling. Magma that reaches the surface is referred to as lava.

Magma chamber: A magma-filled cavity within the lithosphere.

Magnetic anomaly: The value of the local magnetic field remaining after the subtraction of the dipole portion of the Earth's field.

Magnetic north pole: (1) The point where the Earth's surface intersects the axis of the dipole that best approximates the Earth's field. (2) The point where the Earth's magnetic field dips vertically downward.

Magnetic stratigraphy: The study and correlation of polarity epochs and events in the history of the Earth's magnetic field as contained in magnetic strata.

Magnetometer: An instrument for measuring either one orthogonal component or the entire intensity of the Earth's magnetic field at various points.

Mantle: The main bulk of the Earth, between the crust and core, ranging from depths of about 40 to 3480 kilometers. It is composed of dense mafic silicates and divided into concentric layers by phase changes that are caused by the increase in pressure with depth.

Mass spectrometer: An instrument for separating ions of different mass but equal charge (mainly isotopes in geology) and measuring their relative quantities.

Mechanical weathering: The set of all physical processes by which an outcrop is broken up into small particles.

Mesosphere: The lower mantle.

Metamorphism: The changes of mineralogy and texture imposed on a rock by pressure and temperature in the Earth's interior.

Meteorite: A stony or metallic object from inter-planetary space that penetrates the atmosphere to impact on the surface.

Micrometeorite: A meteorite less than 1 millimeter in diameter.

Microstructure: A weak vibration of the ground that can be detected by seismographs and which is caused by waves, wind, or human activity.

Mineral: A naturally occurring element or non-organic compound with a precise chemical formula and a regular internal lattice structure.

Mohorovic discontinuity ("Moho"): Boundary between crust and mantle, marked by a rapid increase in seismic wave velocity to > 8 km/s (depth 5-45 km).

Mohs scale of hardness: An empirical, ascending scale of mineral hardness.
Monocline: A S-shaped fold connecting two horizontal parts of the same stratum at different elevations. Its central limb is usually not overturned.

Moraena: A glacial deposit of till left at the margin of an ice sheet.

Normal fault: A dip-slip fault in which the block above the fault has moved downward relative to the block below.

Oblique-slip fault: A fault that combines some strike slip motion with some dip-slip motion.

Ore: A natural deposit in which a valuable metallic element occurs in high enough concentration to make mining economically feasible.

Orogenic belt: A linear region, often a former geo-syncline, that has been subjected to folding, and other deformation in a mountain-building episode.

Orogeny: The tectonic process in which large areas are folded, thrust-faulted, metamorphosed, and subjected to plutonism. The cycle ends with uplift and the formation of mountains.

Outgassing: The release of juvenile gases to the atmosphere and oceans by volcanism.

Oxidation: A chemical reaction in which electrons are lost from an atom and its charge becomes more positive.

Pahoehoe: A basaltic lava flow with a glassy, smooth, and undulating, orropy surface.

Paleoclimate: The average state or typical conditions of climate during some past geologic period.

Paleomagnetism: The science of the reconstruction of the Earth's ancient magnetic field and the positions of the continents from the evidence of remnant magnetization in ancient rocks.

Paleowind: A prevailing wind direction in an area, inferred from dune structure or the distribution of volcanic ash for one particular time in geologic history.

Pangaea: A great proto-continent from which all present continents have broken off by the mechanism of sea-floor spreading and continental drift.

Pediment: A planar, sloping rock surface forming a ramp up to the front of a mountain range in an arid region. It may be covered locally by thin alluvium.

Preferred orientation: Any deviation from randomness in the distribution of the crystallographic or grain shape axes of minerals of a rock produced by deformation and non-uniform stress during crystallization in metamorphic rocks or by depositional currents in sediments.

P-wave: The primary/fastest wave traveling away from a seismic event through the solid rock, consisting of a train of compressions/dilations of the material.

Pyroclastic rock: A rock formed by the accumulation of fragments of volcanic rock scattered by volcanic explosions.

Radiative transfer: One mechanism for the movement of heat, in which it takes the form of long-wavelength infrared radiation.

Recrystallization: The growth of new mineral grains in a rock at the expense of old grains, which supply the material.

Recumbent fold: An overturned fold with both limbs nearly horizontal.

Regolith: Any solid material lying on top of bedrock. Includes soil, alluvium, and rock fragments weathered from the bedrock.

Relief: The maximum regional difference in elevation.

Remote sensing: The study of Earth surface conditions and materials from airplanes and satellites by means of photography, spectroscopy, or radar.

Rhyolite: The fine-grained volcanic or extrusive equivalent of granite, light brown to gray and compact.

Ridge (mid-oceanic): A major linear elevated landform of the ocean floor, from 200 to 20,000 kilometers in extent. It is not a single ridge, but resembles a mountain range and may have a central rift valley.

Rift valley: A fault trough formed in a divergence zone or other area of tension.

Right-lateral fault: A strike-slip fault on which the displacement of the far block is to the right when viewed from either side.

Ripple: A very small dune of sand or silt whose long dimension is formed at right angles to the current.

Saltation: The movement of sand or fine sediment by short jumps above the ground or stream bed under the influence of a current too weak to keep it permanently suspended.

Sandblasting: A physical weathering process in which rock is eroded by the impact of sand grains carried by the wind, frequently leading to ventifact formation of pebbles and cobbles.

Sandstone: A detrital sedimentary rock composed of grains from 1/16 to 2 millimeters in diameter, dominated in most sandstones by quartz, feldspar, and rock fragments, bound together by a cement of silica, carbonate, or other minerals or a matrix of clay minerals.

Sea-floor spreading: The mechanism by which new sea floor crust is created at ridges in divergence zones and adjacent plates are moved apart to make room.

This process may continue at 0.5 to 10 centimeters/year through many geologic periods.

Secular variation: Slow changes in orientation of the Earth's magnetic field that appear to be long lasting and internal in origin.

Sedimentary rock: A rock formed by the accumulation and cementation of mineral grains transported by wind, water, or ice to the site of deposition or chemically precipitated at the depositional site.

Sedimentary structure: Any structure of a sedimentary or weakly metamorphosed rock that was formed at the time of deposition.

Sedimentation: The process of deposition of mineral grains or precipitates in beds or other accumulations.

Seismic reflection: Mode of seismic prospecting in which a seismic profile is examined for waves that reflected from near-horizontal strata below the surface.

Seismic refraction: Mode of seismic prospecting in which the seismic profile is examined for waves that have been refracted upward from seismic discontinuities below the profile. Greater depths may be reached than through seismic reflection.

Seismic surface wave: A seismic wave that follows the earth's surface only, with a speed less than that of S-waves.

Stratification: A structure of sedimentary rocks, which have recognizable parallel beds of considerable lateral extent.

Stratigraphic sequence: A set of beds deposited that reflects the geologic history of a region.

Stratigraphy: The science of the description, correlation, and classification of strata in sedimentary rocks.

Stratovolcano: A volcanic cone consisting of both lava and pyroclastic rocks, often conical.

Stress: A quantity describing the forces acting on each part of a body in units of force per unit area. Striation: See Glacial striation.

Strike: The angle between true North and the horizontal line contained in any planar feature (inclined bed, dike, fault plane, etc.).

Strike-slip fault: A fault whose relative displacement is purely horizontal.

Subduction zone: A dipping planar zone descending away from a trench and defined by high seismicity, interpreted as the shear zone between a sinking oceanic plate and an overriding plate.

Sublimation: A phase change from the solid to the gaseous state, without passing through the liquid state.

Subsidence: A gentle epeirogenic movement where a broad area of the crust sinks without appreciable deformation.

Syncline: A large fold whose limbs are higher than its center; a fold with the youngest strata in the center.

Tectonics: The study of the movements and deformation of the crust on a large scale, including epeirogeny, metamorphism, folding, faulting, plate tectonics.

Thermal conductivity: A measure of a rock's capacity for heat conduction.

Thermal expansion: The property of increasing in volume as a result of an increase in internal temperature.

Thermoremanent magnetization: Permanent magnetization acquired by igneous rocks in the Earth's magnetic field as they cool through the Curie point.

Thrust fault: A dip-slip fault in which the upper block above the fault plane moves up and over the lower block, so that older strata are placed over younger.
Till: An unconsolidated sediment containing all sizes of fragments from clay to boulders deposited by glacial action, usually unbedded.

Topography: The shape of the Earth's surface, above and below sea level; the set of landforms in a region; the distribution of elevations.

Topset bed: A horizontal sedimentary bed formed at the top of a delta and overlying the foreset beds.

Trace element: An element that appears in minerals in a concentration of less than 1 percent (often less than 0.001 percent).

Transform fault: A strike-slip fault connecting the ends of an offset in a mid-ocean ridge. Some pairs of plates slide past each other along transform faults.

Transverse dune: A dune that has its axis transverse to the prevailing winds or to a current.

Trench: A long and narrow deep trough in the sea floor; interpreted as marking the line along which a plate bends down into a subduction zone.

Tuff: A consolidated rock composed of pyroclastic fragments and fine ash. If particles are melted slightly together from their own heat, it is a "welded tuff."

Turbulent flow: A high-velocity flow in which streamlines are neither parallel nor straight but curled into small tight eddies (compare Laminar flow).

Ultramafic rock: An igneous rock consisting dominantly of mafic minerals, containing less than 10 percent feldspar.

Unconformity: A surface that separates two strata.

Unconsolidated material: Non-lithified sediment that has no mineral cement or matrix binding its grains.

Uplift: A broad and gentle epeirogenic increase in the elevation of a region without a eustatic change of sea level.

Vadose zone: The region in the ground between the surface and the water table in which pores are not filled with water. Also called the unsaturated zone.

Valley glacier: A glacier that is smaller than a continental glacier or an icecap, and which flows mainly along well-defined valleys, many with tributaries.

Vein: A deposit of foreign minerals within a rock fracture or joint.

Ventifact: A rock that exhibits the effects of sand-blasting or "snowblasting" on its surfaces, which become flat with sharp edges in between.

Vesicle: A cavity in an igneous rock that was formerly occupied by a bubble of escaping gas.

Viscosity: A measure of resistance to flow in a liquid.

Volcanic ash: A volcanic sediment of rock fragments, usually glass, less than 4 mm in diameter, formed when escaping gases force out a fine spray of magma.

Volcanic bomb: A pyroclastic rock fragment that shows the effects of cooling in flight in its streamlined or "bread-crust" surface.

Volcanic breccia: A pyroclastic rock in which all fragments are more than 2 millimeters in diameter.

Volcanic cone: The deposit of lava and pyroclastic materials that has settled close to the volcano's central vent.

Volcanic dome: A rounded accumulation around a volcanic vent of congealed lava too viscous to flow away quickly; hence usually rhyolite lava.

Volcanic ejecta blanket: A collective term for all the pyroclastic rocks deposited around a volcano, especially by a volcanic explosion.

Volcano: Any opening through the crust that has allowed magma to reach the surface, including the deposits immediately surrounding this vent.

Warping: In tectonics, refers to the gentle, regional bending of the crust, which occurs in epeirogenic movements.

Water table: A curved surface below the ground at which the vadose zone ends and the phreatic zone begins; the level to which a well would fill with water.

Weathering: The set of all processes that decay and break up bedrock, by a combination of physically fracturing or chemical decomposition.

Xenolith: A piece of country rock found engulfed in an intrusion.