Lunar and Planetary Laboratory
Department of Planetary Sciences

Yellowstone!

a trip to Montana, Wyoming, and Idaho
for comparative planetary geology and biology

Planetary Geology Field Practicum

Ptys. 594a

Fall 1997

versity of Arizona
Arizona

We dedicate this handout to the following people:

Mike Drake
for his assistance, financial and otherwise

David Kring
for organizing and scouting

Jay Melosh
for directing the trip

Chris Chyba
for the origins connection

Carolyn Palmer
for keeping us all on track

THANK YOU VERY MUCH!!

the trip participants

Some Remarks and Other Stuff

A field trip to Yellowstone National Park offers a fantastic opportunity to study a set of comparative planetary geology topics that would be unavailable at any other site. The combination of areas of geologic interest within driving distance of Yellowstone that have a direct planetary comparison is quite high, and probably to be unequaled by any other field trip. We will have the opportunity to gain a more intuitive understanding of the working of geysers and volcanoes in outer solar system bodies, the effects of hydrothermal alteration possibly pertinent to Mars and asteroids, as well as tectonic processes in action throughout the solar system.

Of particular interest is the biology of the hot springs and vents in Yellowstone. Life in these extreme climates may be akin to that which might have existed in hydrothermal vents on Mars, and may well represent the most deeply rooted organisms we know. We can see the low temperature carbonate limestones, and discuss how carbonates are formed by both life and non-living mechanisms. Seeing the vents and rocks first hand and being able to observe the conditions under which this life exists will assist us in understanding the arguments for and against past life on Mars, and better able to assess the literature presented in this area. We will be aided in this by the presentations of guest speakers who are experts in this field. No other possible field trip destination will be able to provide such a rich background for discussing and understanding the origins of life here on Earth, and possibly other planets.

Obviously, geysers will only be accessible to students on a Yellowstone field trip. They offer the unique chance for examination of eruption processes on Io and Triton. We will get a first hand look at geysers in action, and hopefully attain a better understanding of the types, similarities and differences of past and present eruptions on Io, Triton, Mars, Earth, etc. In addition, the study of the sulfurous chemistry of the hot springs and sulfur pits will allow all of us to better grasp the rheology of sulfur rich geologic processes and chemistry on Io.

This is all in addition to the volcanic activity, earthquakes, calderas, glacial features, various types of lava flows and tuffs, obsidian cliffs, mountain building, fluvial action and erosion etc., that can all be found all in this one place.

Due to the unique nature of the trip, and the myriad opportunities that it presents, several changes and additions to our usual field trip protocol have been made. **David Kring** will be heading out to the Park several days early to scout out the sites for talks, and to be sure necessary roads, etc. are open. We will begin formally discussing science two days before we actually leave. Four students will present overview talks in a two hour session on Monday the 15th, from 5 to 7pm. This will allow us to get the very most out of the trip, as all subsequent talks and information gained while at the park can be put into immediate context. **Elizabeth Turtle** will begin by discussing the general stratigraphy and volcanic history of the park, followed by **Barb Cohen** with an overview of the geyser activity, **David Trilling** talking about the general aspects of life and biology at Yellowstone, and **Kim Cyr** giving a presentation on glacial history and features of the park.

On the trip itself, the first talk will be given by **David Trilling**. This groundbreaking (or ground-avoiding) trip will be on the geology seen from the air between Tucson and Bozeman. Since this is the first time we are flying to a field trip destination, this is the first chance for a talk such as this one. We will then hear about several fascinating topics, as detailed in the following itinerary, with the addition of a talk by **Jorge Pastoriza**, speaking on biology and life. Other changes from usual trips include a more involved and extended field trip handout, possibly getting filmed for a public television show, the possibility of eating some meals out at the local restaurant or cafeteria, staying in the same camping area for the entire trip and more. Now on to the itinerary ...

Yellowstone National Park

Planetary Geology Field Practicum Ptys 594a
Fall 1997, September 17th - 22nd

Contents

PTYS 594a,
PLANETARY FIELD GEOLOGY PRACTICUM

Fall 1997 Yellowstone Itinerary

Wednesday, 17 Sept.

6:50 am	Depart Tucson Internationa airport at 6:40 on Delta Airlines flight #1862 to Bozeman MT via. Salt Lake City.
12:22 pm	Arrive Bozeman MT. Pick up vehicles, buy groceries
3:30 pm	Depart Bozeman for Yellowstone
5:00 pm	Arrive Gardiner gate, Yellowstone National Park
7:30 pm	Arrive at Grant Village campground, cook dinner, camp

Thursday, 18 Sept.

7:00 am	Break camp, drive to north-east portion of park Columnar Jointing by **Joe Spitale**. Stop at Sheepeater Cliffs Glaciers on Earth and Mars by **Doug Dawson**. Stop just E. of Tower Junction Bimodal Volcanism by **Peter Lanagan**. Fossil forests by **Nancy Chabot**. Stop at Specimin Ridge overlook Heart mountain fault by **Rachel Mastrapa**. Stops at E. Gate and Cathedral Cliffs. River downcutting at Yellowstone river gorge, more columnar jointing by **Eric Wegryn** and Joe Spitale. Stop S of Tower Junction Remote sensing of hydrothermally altered rocks by **Peter Smith**. Sample collection by Jim Head.
8:30 pm	Fireside discussion on wildlife lead by **Barbara Cohen** History of Yellowstone Park by **Eric Weygren**.

Friday, 19 Sept.

7:00 am	Break camp, drive to north-west portion of park Physics of caldera resurgence by **Vladimir Florenski**. Stops at rapids near Fishing Village and near Canyon Junction. Chemistry and isotopes of Yellowstone's hot water by **Jim Head**. Stop at Mud volcano. Yellowstone Caldera overview by **Janet McLarty**. Stops near Dunraven pass and Tuff Cliff near Madison Junction Madison Canyon landslide by **Cynthia Phillips**. Stop at visitor center on the landslide Landslides on Earth and the other planets by **Josh Emery.**
8:30 pm	Fireside chat on 1988 Forest Fires by **Luba Florenski.**

Saturday, 20 Sept.

7:00 am Break camp, drive to west portion of park

Prediction of volcanic eruptions by **Jennifer Grier**. Stop at small resurgent dome near campsite.

Hydrothermal Chemistry by **Barbara Cohen** and **Jim Head**. Stops at Fountain Paint Pots, Mammoth Hot Springs and Midway Geyser Basin.

Origin of life by **Chris Chyba**.

We will be joined by experts on life and hot water, **Dave DesMarais** and **Anna-Louise Reysenbach**. We will also be filmed as part of a documentary by Kurtis productions, who also wants to catch a "fireside chat", or round-robin discussion of life on other planets later in the evening.

Sunday, 21 Sept.

7:00 am Break camp, return to west portion of park

Glaciers and volcanic eruptions by **Andy Rivkin**. Stop at Pocket Basin.

Physics of Geysers by **Ralph Lorenz**. Stop at Norris Geyser Basin

Earthquakes and Geysers by **Dave Wood**. Stop at Midway Basin

Planetary Geysers by **Greg Hoppa**. Stop at Old Faithful

8:30 pm Fireside chat on Geothermal Energy extraction by **Rob Coker**.

Monday, 22 Sept.

7:00 am Break camp, drive straight to Bozeman

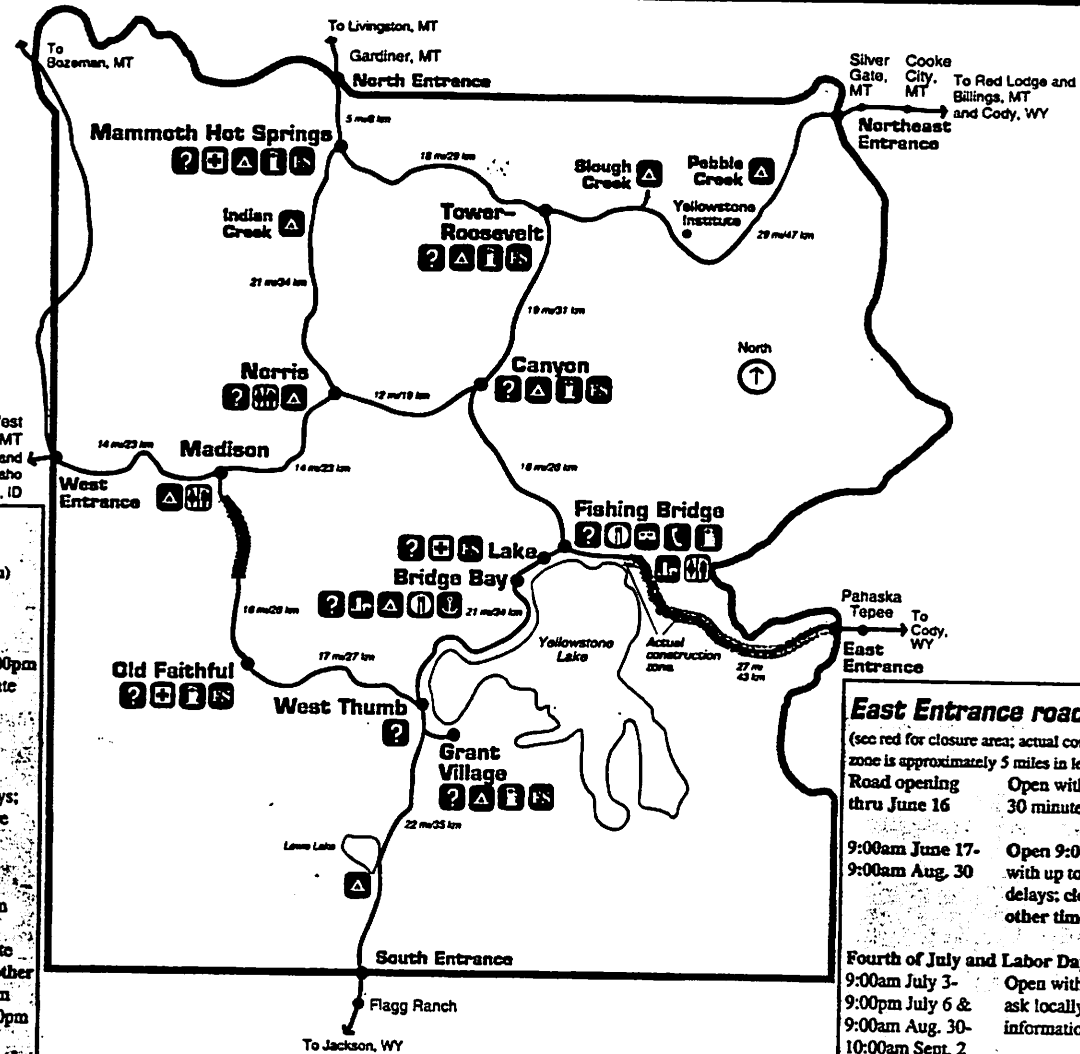
1:10 pm Depart Bozeman, Delta Airlines flight #1190 via Salt Lake City and Phoenix

6:18 pm Arrive Tucson International Airport, go home

Primary Drivers: Chyba, Cohen, Grier, Dawson, Kring, Spitale, Turtle

Distribution:

N. Chabot
C. Chyba
B. Cohen
R. Coker
K. Cyr
D. Dawson
J. Emery
V. Florensky
J. Grier
J. Head
G. Hoppa
D. Kring
P. Lanagan
R. Lorenz
J. McLarty
R. Mastrapa
J. Melosh
C. Palmer
J. Pastoriza
C. Porco
C. Phillips
A. Rivkin
P. Smith
J. Spitale
D. Trilling
E. Turtle
E. Wegryn
D. Wood



Madison—Old Faithful road work (see red for closure area)

Road opening thru June 1	Open with up to 30 minute delays.
9:00am June 2-9:00am Aug. 30	Open 9:00am-9:00pm with up to 30 minute delays; closed all other times.
Fourth of July and Labor Day	
9:00am July 3-9:00pm July 6 & 9:00am Aug. 30-10:00am Sept. 2	Open without delays; ask locally for more information.
Sept. 2-30	Open 6:00-10:00am and 6:00-10:00pm with up to 30 minute delays; closed all other times. Open 6:00am Saturday thru 10:00pm Sunday with up to 30 minute delays.
8:00am Oct. 1	Closed for the season.

East Entrance road work

(see red for closure area; actual construction zone is approximately 5 miles in length)

Road opening thru June 16	Open with up to 30 minute delays.
9:00am June 17-9:00am Aug. 30	Open 9:00am-9:00pm with up to 30 minute delays; closed all other times.
Fourth of July and Labor Day	
9:00am July 3-9:00pm July 6 & 9:00am Aug. 30-10:00am Sept. 2	Open without delays; ask locally for more information.
Sept. 2-Nov. 2	Open 6:00-10:00am and 6:00-10:00pm with up to 30 minute delays; closed all other times.
8:00am Nov. 3	Closed for the season.

Yellowstone roads and facilities

This map shows summer roads/facilities; see page 7 for dates of operation in spring or autumn. Winter visitors: please call for a winter information packet.

- Visitor center, ranger station, or info station
- General store
- Food service
- Gasoline/fuel
- Marina
- Clinic or hospital
- Restroom
- Campground
- Campground (hard-sided vehicles)
- Full services (includes lodging, food service, store, rest rooms, phone)

Important numbers

Yellowstone info: (307) 344-7381
TDD (Telecommunications Device for the Deaf only): (307) 344-2386
Lodging info: (307) 344-7311
Lodging TDD: (307) 344-5395
Yellowstone home page: http://www.nps.gov/yell/index.htm

Entrance fees have changed in Yellowstone National Park; see page 2.

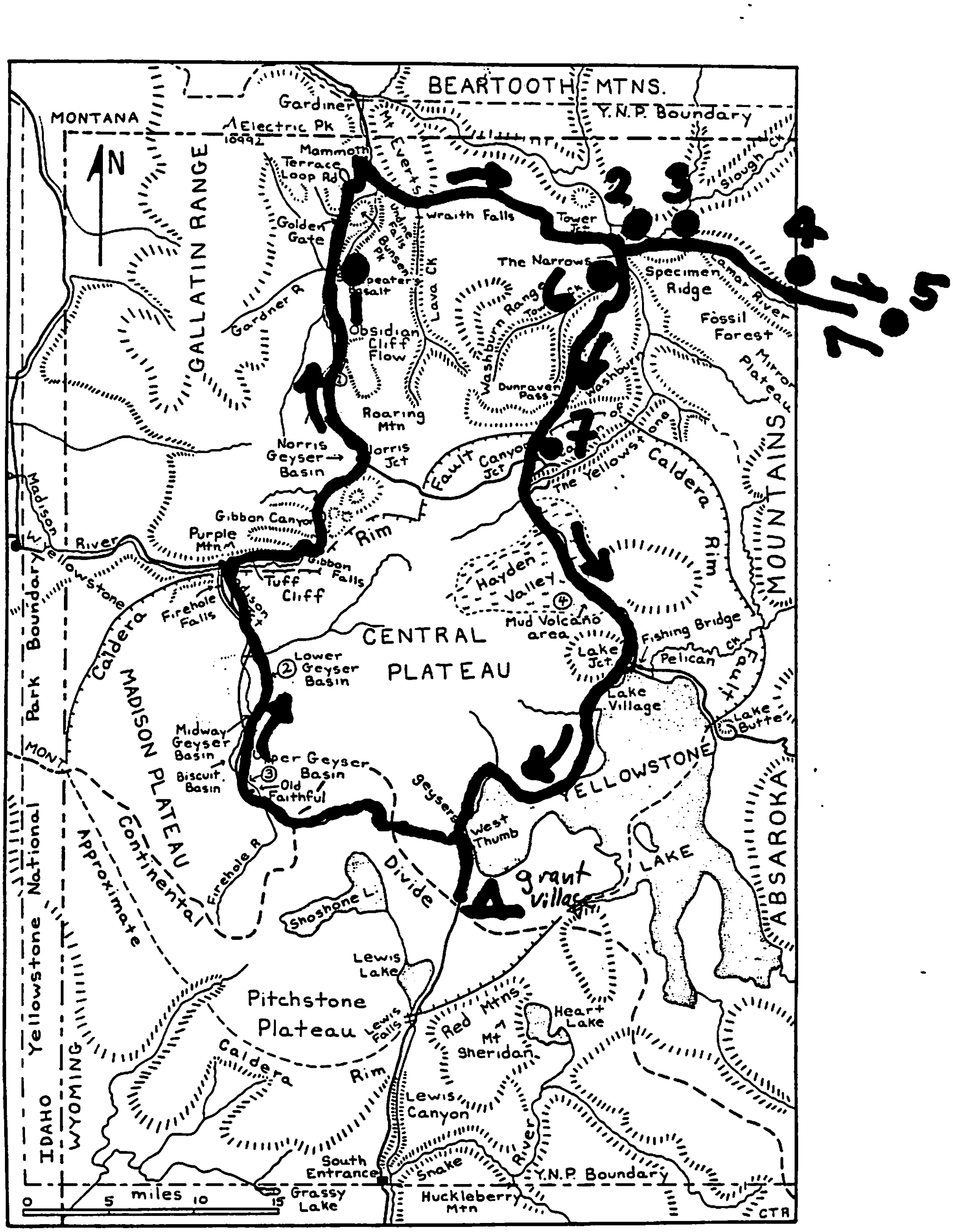


Figure 3.18. Map of Yellowstone National Park showing points of geological interest along the loop roads, Log 15.

Day 1
Thursday

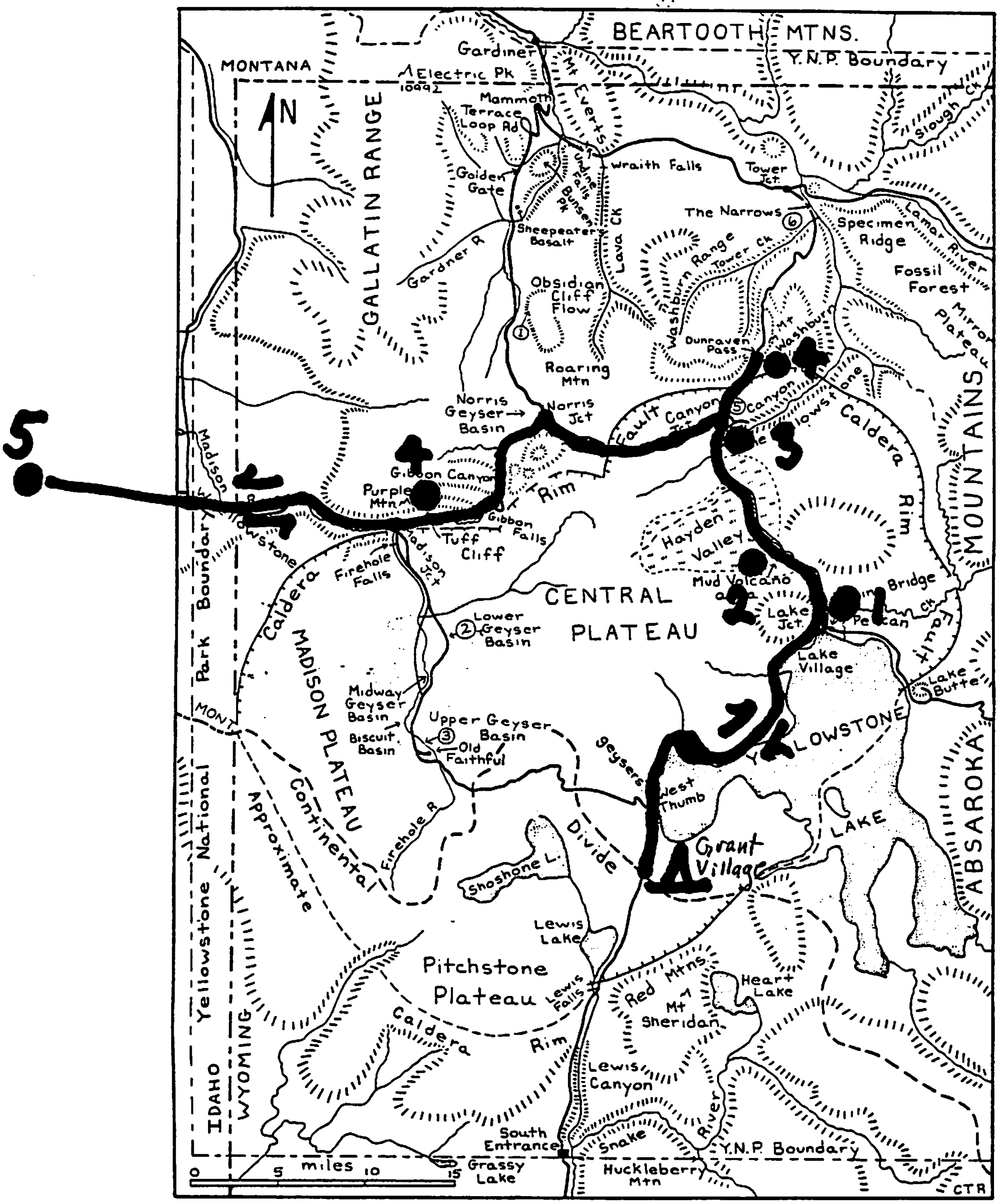


Figure 3.18. Map of Yellowstone National Park showing points of geological interest along the loop roads, Log 15.

Day 2

Friday

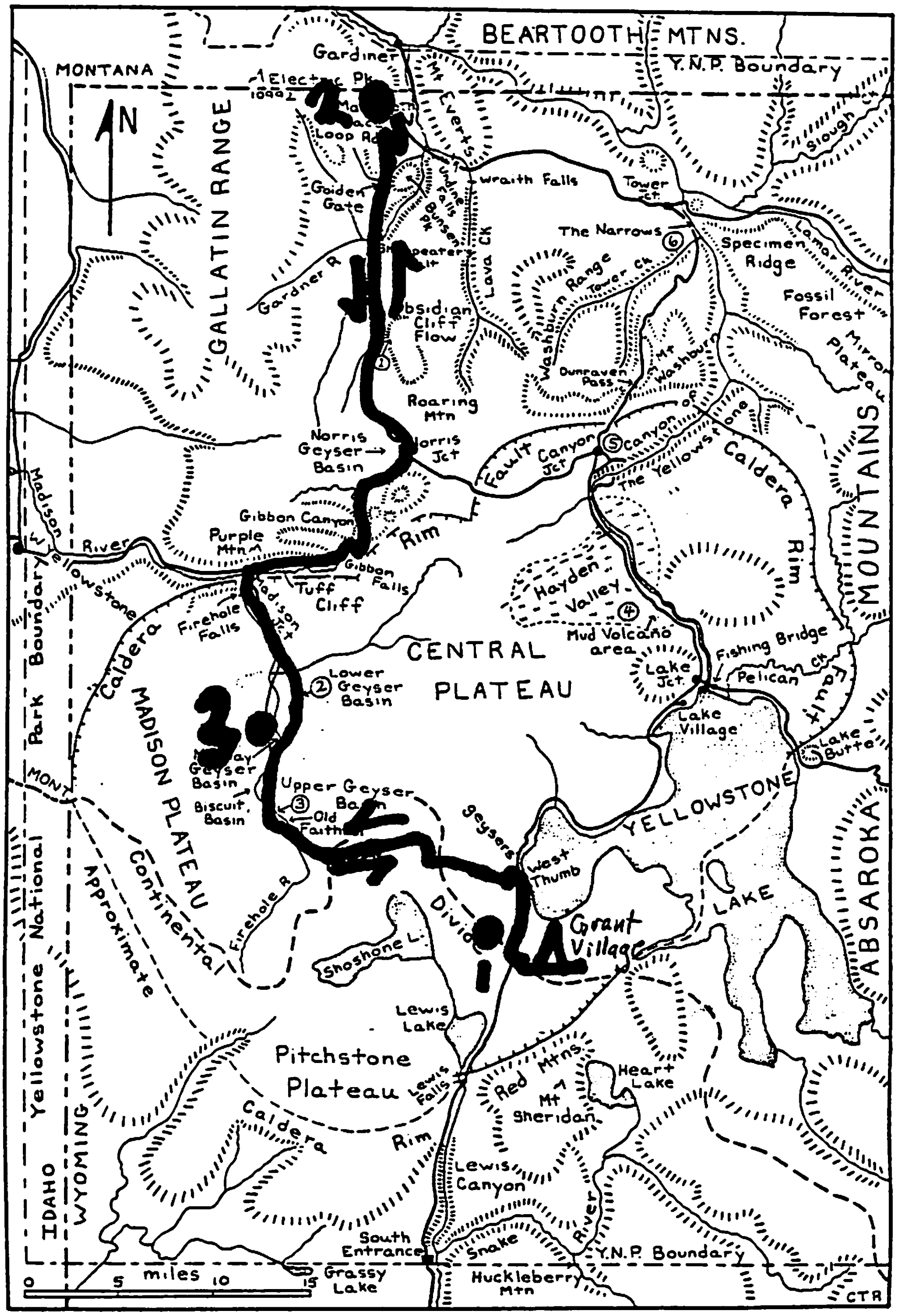


Figure 3.18. Map of Yellowstone National Park showing points of geological interest along the loop roads, Log 15.

Day 3

Saturday

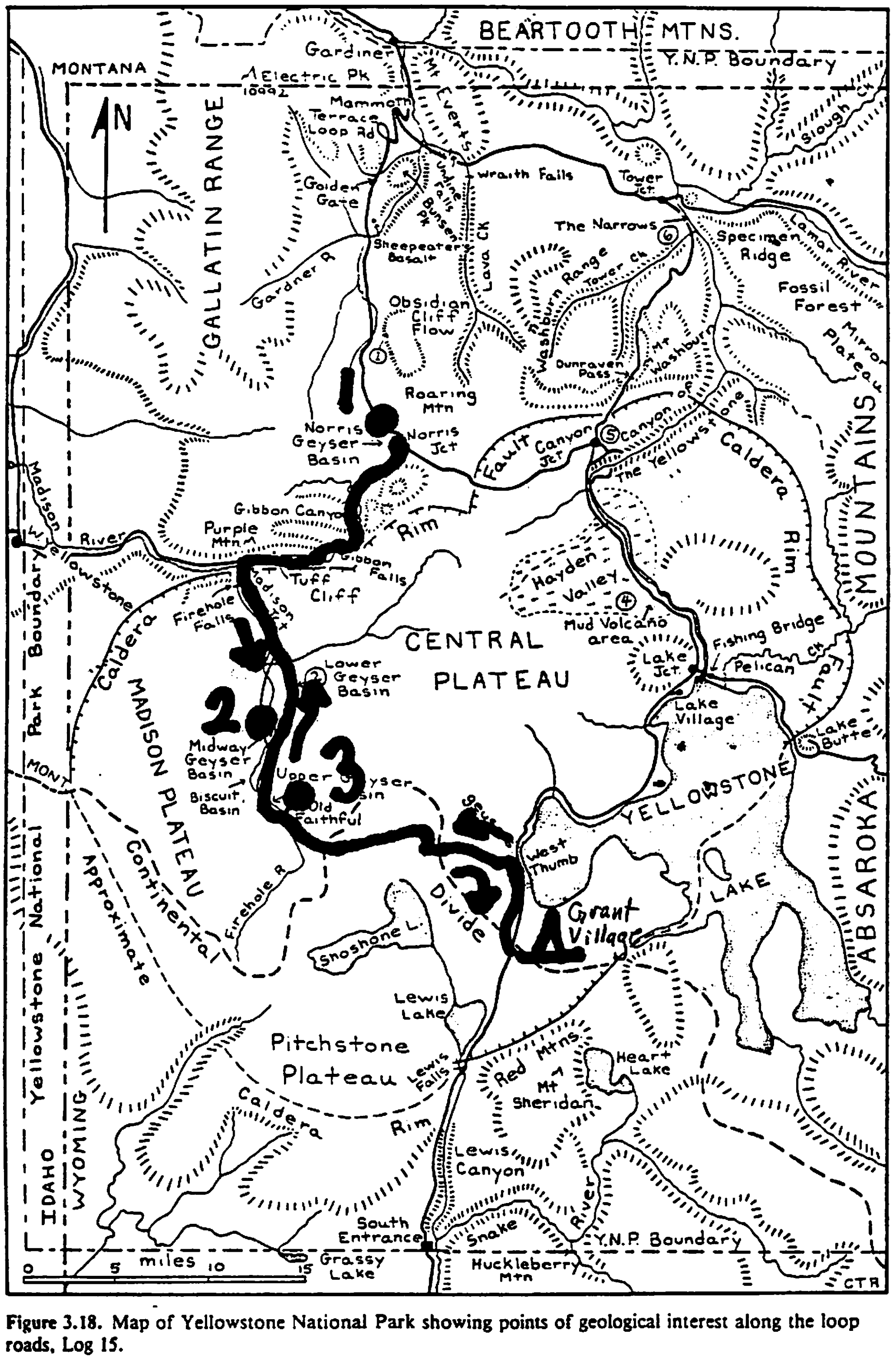


Figure 3.18. Map of Yellowstone National Park showing points of geological interest along the loop roads, Log 15.

Day 4

Sunday

RESEARCHER SAFETY

Research in Yellowstone is frequently conducted in places that are off limits to or not often used by regular visitors. For this reason, a safety bulletin for research scientists is included with the permit application package.

1. Safety First: Personal safety and preservation of park resources must take precedence over your research project. Never work alone in the backcountry and do not take chances. Remember, in remote areas such as Yellowstone, a small mishap can potentially lead to serious consequences.

2. Notify the local District Ranger(s) before conducting field work: District Rangers are responsible for any problems resulting from your activities. They will best be able to react if well informed about your activities. The presence of an unknown researcher's vehicle at a trailhead is cause for concern for the visitor protection staff.

3. Wildlife interactions: Encounters with bears in Yellowstone have resulted in injury or death to both people and bears. Please follow Bear Management guidelines that are included in your permit package. Other dangerous wildlife include bison, moose, and elk, all of which will aggressively protect themselves or their young if you intrude into their space. A minimum of 100 yards must be maintained from bears (a minimum of 25 yards for other wildlife).

4. Hypothermia: This condition is a leading safety hazard often brought about by cold, wet conditions. It results in the loss of coherence, shivering, and unconsciousness. Stay dry to stay warm. Be prepared for the worst weather conditions. Hyperthermia can strike during any time of the year in Yellowstone.

5. Avalanche: Avalanches kill people in the mountains every year. Even a small snowslide could prove deadly if you are knocked unconscious. People have died buried under less than a foot of snow. A companion could save your life, never work alone. If your are working during winter, be knowledgeable about avalanche risk and procedures.

6. Geothermal burns: Thermal pools are as deadly as they are beautiful. At least 18 people have died from falling into hot water in Yellowstone. Thin crust, especially in acid sulfate areas subject to erosion and collapse, are especially hazardous.

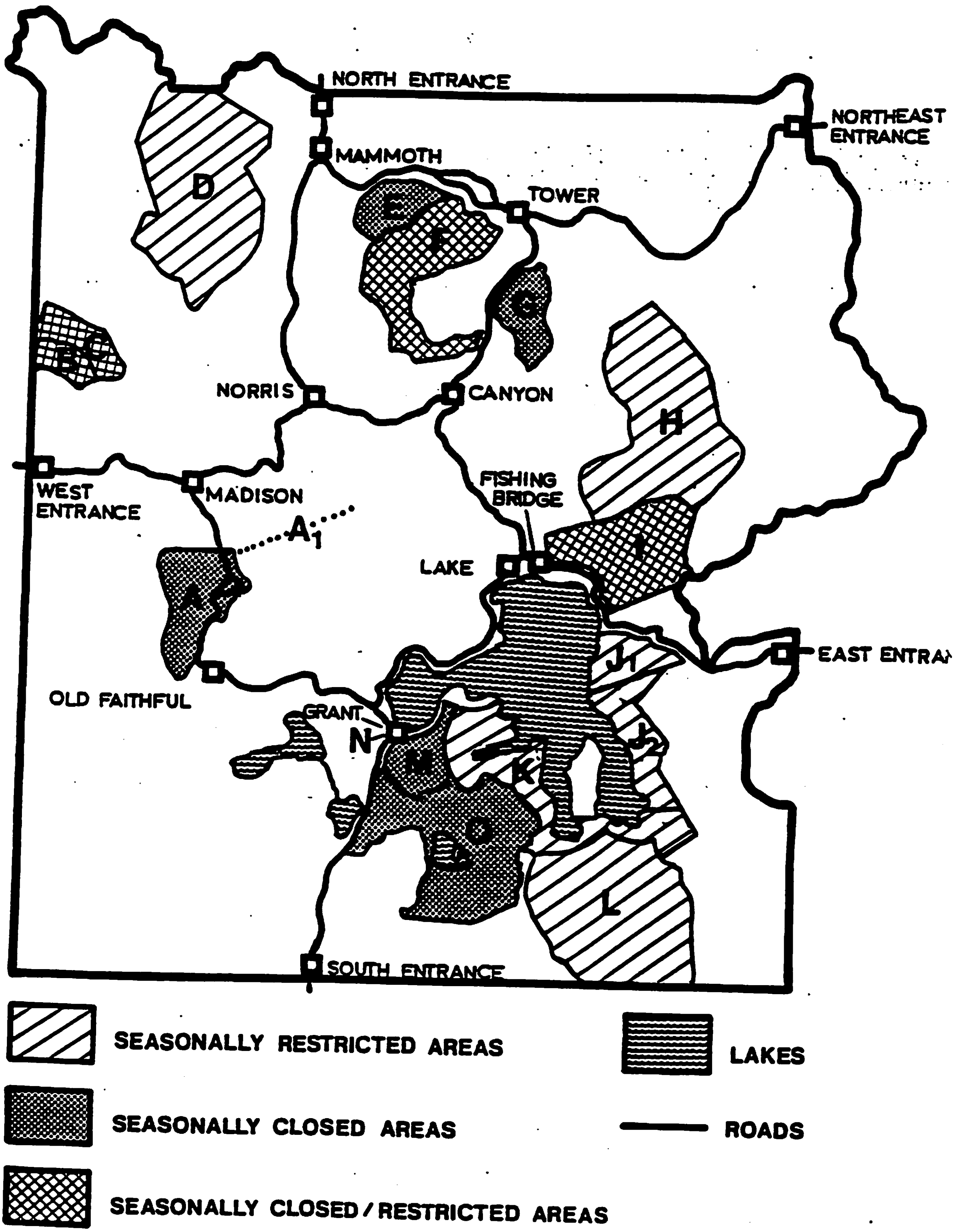
7. Anoxic conditions: In geological depressions such as sink holes at the Mammoth Terraces, be aware of the concentration of odorless, heavier than air gases such as CO_2 and CO, which can crowd out oxygen and cause asphyxiation. Have a companion monitoring your activities from a safe location. Concentrations of distilled hydrocarbons at Calcite Springs can cause headache or dizziness; stay no more than an hour in this area and do not visit this area alone.

8. Vehicles: Probably the most important safety message about Yellowstone is that visitors are on vacation and often are not paying attention to their driving. Because of this, visitors often stop their vehicle on a blind curve, blocking the road. Drive defensively and plan on a slow trip through Yellowstone during the summer field season.

Please feel free to discuss these issues or report any concerns about safety to the local ranger or the research coordinator.

BEAR MANAGEMENT AREAS

Purpose: To reduce human related impacts on bears in high density grizzly bear habitat. Eliminating huma entry and disturbance in specific areas prevents human/bear conflicts and provides areas where bears can pursue natural behavioral patterns and other social activities free from human disturbance. Types of restrictions include: Area closures, trail closures, a minimum party size of four or more people, and tra limited to daylight hours or to established trails.



BEAR MANAGEMENT AREAS

A. **Firehole**: Area (includes Firehole Freight Road and Firehole Lake Road) is closed March through the Friday of Memorial Day weekend. The Mary Mountain Trail from the Nez Pe trailhead to Mary Lake is closed March 10 through June 15. Through travel from the Can trailhead is not allowed, however, travel is allowed from the Canyon trailhead to Mary Lo and back. Streamside use is allowed from the point where Nez Perce Creek crosses the ma road to a point one mile upstream along Nez Perce Creek.

B. **Richard's Pond**: Area is closed March 10 through the Friday of Memorial Day weekend. F the Saturday of Memorial Day weekend through September 30, Duck Creek, from the park bounda upstream to the Campanula Creek/Richards Creek fork, is open to streamside travel. The a upstream from Campanula Creek/Richard's Creek fork is closed from March 10 through Septem 30.

C. **Gneiss Creek**: Area is closed March 10 through June 30. From July 1 through November travel is allowed only on designated trails (off-trail travel is prohibited).

D. **Gallatin**: From May 1 through November 10, travel is allowed only on designated trai (off-trail travel is prohibited). A minimum group size of four or more is recommended hiking and camping.

E. **Blacktail**: Area is closed March 10 through June 30.

F. **Washburn**: Area is closed August 1 through November 10. From March 10 through July 31, t area is open by special permit only. Contact the Tower Ranger Station for perm information.

G. **Antelope**: Area is closed March 10 through November 10. The Dunraven Road and relat turnouts are open. From May 25 through November 10, foot travel is allowed on the old Ro Trail from Tower Falls Campground to the Buffalo Picnic Area.

H. **Mirror Plateau**: From May 15 through November 10, the area is open to day use only with t exception that from July 1 through August 14 overnight camping is permitted for a combin total of 14 nights per summer at the 301 and 5P7 campsites.

I. **Pelican Valley**: Area is closed April 1 through July 3. From July 4 through November 1 the area is open to day-use only between the hours of 9 a.m. and 7 p.m.

J. **Clear Creek**: Area J1 - From April 1 through August 10, travel is only allowed on the ea shore from Nine-mile trailhead to Park Point. All other trails are closed and off-tra travel is prohibited. On August 11, all other campsites are open and off-trail travel permitted.
Area J2 - From April 1 through July 14, travel is only allowed on the east shore trail fr Park Point to Beaverdam Creek. All other trails are closed and off-trail travel prohibited. Open campsites are 5E3, 5E4, 5E6, and 5E8 (no travel away from campsite). A other campsites are closed. On July 15, all campsites open and off-trail travel i permitted.

K. **Lake Spawn**: From may 15 through July 14, no off-trail travel allowed and the tra between Cabin Creek and Outlet Creek is closed. Open Campsites are 7L5, 7L6, 7L7, 7M3, 7M4 6A3, and 6B1 (no travel away from campsite). On July 15 all campsites open and off trai travel is permitted.

L. **Two Ocean**: From March 10 through July 14 and August 22 through November 10 , travel i allowed only on designated trails (off-trail travel is prohibited). From July 15 throug August 21, a permit is required for persons wishing to travel away from designated trail Contact the South Entrance Ranger Station for permit information.

M. **Riddle/Solution**: Area is closed April 30 through July 14.

N. **Grant Village**: Campground opens June 20 or earlier if bear use of the area spawni streams is over prior to that time. If bears are still frequenting the spawning stream after June 20, the campground loops adjacent to the stream(s) will remain closed until bea activity ceases. Campground closes October 16.

O. **Heart Lake**: Area is closed April 1 through June 30.

INFORMATION PAPER NO. 11
(Revised March 1996)
U.S. Department of the Interior
National Park Service
Yellowstone National Park

REMINDERS TO RESEARCHERS

The following notes are memory jogs for us, as well as for you. With them, we hope to make your work in the park go as smoothly as possible.

1. Wherever you work in Yellowstone, you must contact the ranger in charge of the area. He or she is responsible for whatever goes on in the district and will want to know about your project and its effect (if any) upon National Park Service operations. He or she is a key person in the National Park Service-researcher liaison. A list of these people is enclosed. You may be assigned a specific person to provide liaison in the park. Whether this is the case, or you are on your own, you or your liaison must contact the area ranger.

2. Contrary to information on some maps, there are few service roads of any length still in existence. What few exist are locked off; see the area ranger about use of specific roads.

3. No one is permitted to drive off designated roads.

4. Wheeled vehicles are not permitted on park trails. In winter, remember snowmobile regulations prohibit off-road travel.

5. You will need a backcountry permit for any overnight backcountry work, again see the area ranger. You are expected to abide by all rules and regulations required of humans, including things like bringing out any nonburnable trash such as cans and bottles.

6. Saddle stock and pack outfits, may be rented from T.W. Services or from suppliers outside the pad (N.P.S. stock is ordinarily not available). Occasionally, your stock may be kept in Government corrals - contact the area ranger. There may be a charge for use of Government corrals. Commercial stock outfitters must have a limited concessionaires permit to operate in the Park.

7. When collecting specimens in public use areas, in the few cases in which this is authorized, collecting must be at dawn or at dusk to minimize the number of people who may see you. Not everyone realizes that special permission is needed to collect in the park. Sometimes a visitor will see a researcher collecting in the park and think that such may be done by anyone or that illegal activity is in progress. Again, be sure to contact the area ranger prior to each collecting period.

8. Report all bear sightings to the area ranger as soon as possible. We want to remind you that you are working in bear country. Grizzly and black bears are dangerous animals, but they are a part of Yellowstone's environment. Your laboratory is their home. We are, also, very interested in sightings of other species. Please review the enclosed Sightings of Interest

informational sheet.

9. Bear management areas have been designated to reduce or eliminate human-related impacts in high density grizzly bear habitat. Generally, you will not be exempted from these closures. These may change from year to year. We will provide the most up-to-date information that we have regarding these areas. Again, the area ranger is your best source.

10. Low-level aerial flights of less than 500 feet, route to be used, and landing (helicopter) in the park must be cleared with the Superintendent's Office. Supply details with request to the Research Office, who will then pass the information on to the Chief Ranger's Office for decision.

11. If you plan to use the campgrounds, remember that the time limits established for visitors also apply to researchers. In general, these time limits are 2 weeks from Memorial Day to Labor Day and 30 days during the rest of the year.

12. Park housing is extremely limited. You should either make your requests for the same six months in advance or make arrangements for alternative facilities.

13. Don't be afraid to ask questions! You can't be expected to know all park regulations, so talk over your work plans with the area rangers. They will gladly help you plan your research within the framework of law and policy which governs the administration of Yellowstone.

14. Any research materials left at end of season must be removed unless specifically authorized to remain on-site.

TABLE OF IGNEOUS ROCKS (Parsons, 1978)

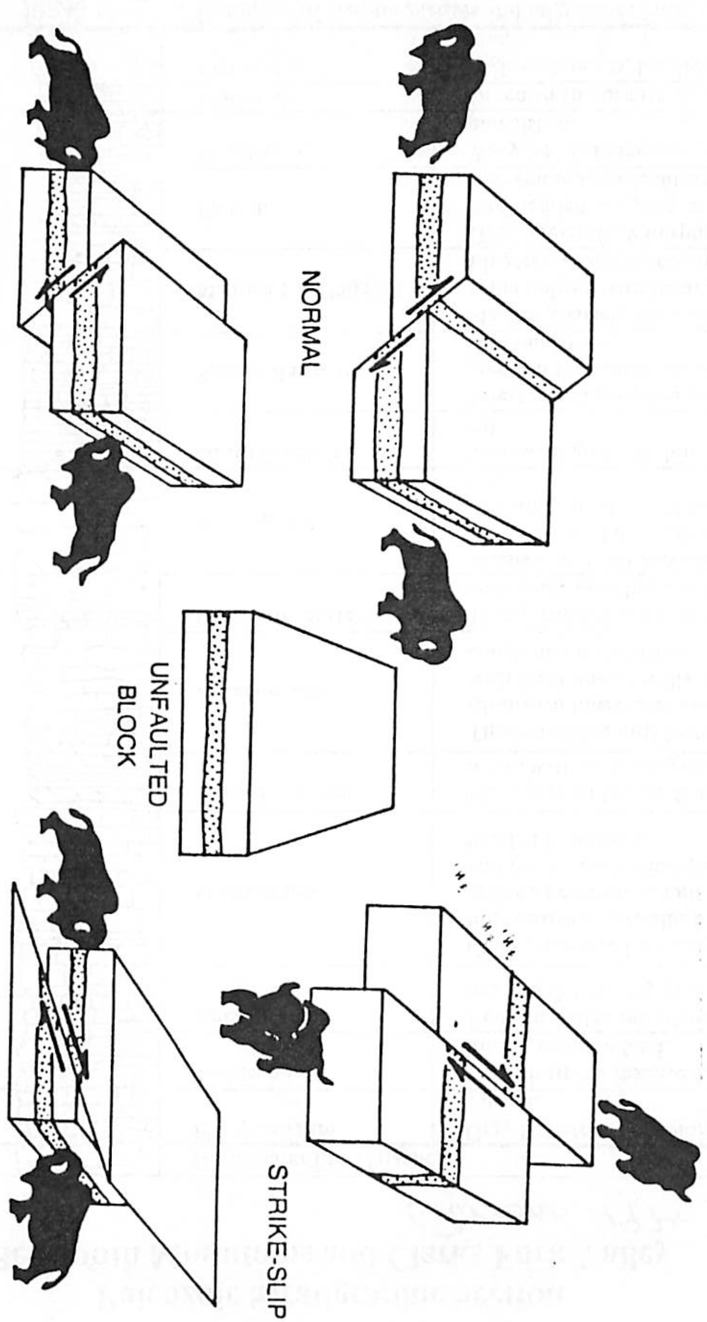
Color and Mineral Composition	Crystallized at Depth: Coarse-Grained	Solidified on or Near Surface: (Volcanic) Fine-Grained and/or Glassy
Light-colored minerals predominate: quartz, orthoclase feldspar, small amounts of mica and/or hornblende	Granite	Rhyolite Obsidian (glass)
Intermediate in color: two feldspars; hornblende	Diorite Monzonite	Andesite
Dark-colored minerals predominate: plagioclase feldspar, augite, and/or olivine	Gabbro	Basalt
Pyroxenes and/or olivine: no feldspars	Ultra-mafic rocks	—

TABLE OF SEDIMENTARY ROCKS

Sediments or Particles	Rocks	Composition
Pebbles, gravel	Conglomerate	Various rocks
Sand	Sandstone	Usually quartz, but various others
Silt	Siltstone	Usually quartz
Mud, clay	Shale	Clay minerals
$CaCO_3$ precipitates	Limestone and dolomite	Calcite (dolomite)
$CaSO_4$ precipitates	Gypsum	Gypsum

TABLE OF METAMORPHIC ROCKS

	Rock Name	Mineral Composition	Commonly Derived from
Foliated	Slate	Micas, etc.	Shales
or	Schist	Micas, hornblende, garnet, quartz	Fine-grained igneous rocks; silt, shales
Layered	Gneiss	Feldspar, quartz, hornblende, etc.	Many coarse-grained rocks; igneous + conglomerate
	Amphibolite	Hornblende, (trace of feldspar, quartz)	Basalts; iron-rich sediments
Nonfoliated	Quartzite	Quartz	Conglomerates and sandstones
or	Marble	Calcite, dolomite	Limestones or dolomites
Massive	Serpentinite	Serpentine	Ultramafic igneous rocks

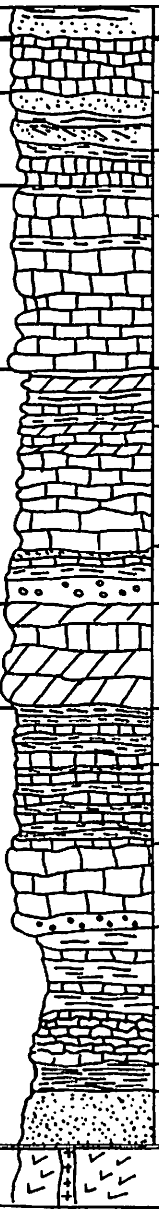


Types of faults: bison push/pulls show how forces act to produce the different types of faults.

Appendix A.2

Paleozoic Stratigraphic Section
Beartooth Mountains and Clarks Fork Valley

(Parsons, 1974)



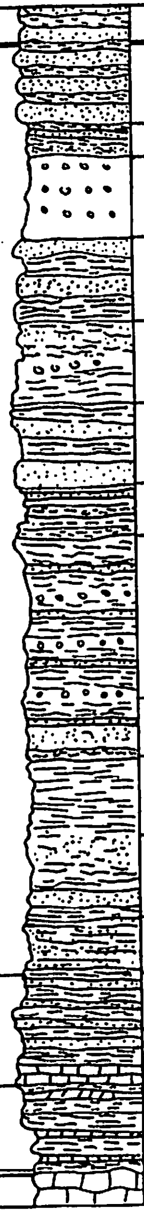
	(Chugwater fm.–Triassic)	
Permian	Phosphoria fm.	Gray limestones & dolomites, + calc. ss.
Pennsylvanian ?	Tensleep ss.	Grayish to tan massive sandstones, locally cross-bedded.
	Amsden fm.	Reddish shales and siltstones, + gray lms and dol; locally gray cherty ss.
Mississippian	Madison lms.	Chiefly massive light-gray to tan and buff coarsely crystalline to fine-grained limestones, some dolomites and local cherty zones; a few thinly-bedded limestones.
Devonian	Three Forks fm.	Platy gray to brown & yellowish dol & lms with some grayish-green sh.
	Jefferson lms.	Thinly-bedded buff-brown to grayish-brown limestones and dolomites with fetid odor; locally sandy or conglomeratic at base.
	Beartooth Butte fm.	Thinly-bedded red & buff limy shale with some gray lms and basal lms cgl.
Ordovician	Bighorn Dol.	Massive, mottled grayish-buff to cream-colored dol with a middle unit of mainly thinly-bedded fine-grained lms.
Cambrian	Grove Creek fm.	Yellowish-green sh, lms & intraform cgl.
	Snowy Range fm.	Interbedded grayish-green shales & greenish intraform cgl, with few thin sandstones.
	Maurice fm. (Pilgrim)	Massive coarsely xln limestones, some oolitic, with basal unit of grayish-green coarse intraform cgl & sh.
	Park sh	Gray, greenish, & purplish sh with interbedded tan platy ss & sltst; some fine-grained lms & intrafm cgl.
	Meagher lms.	Wavy-bedded limestones; some greenish sh.
	Wolsey sh.	Greenish to purplish shales.
	Flathead ss.	Light-colored ss, locally conglomeratic.
Precambrian	(Complex of granitic gneisses and migmatites intruded by mafic dikes, etc.)	

Vertical scale: 1 inch = approximately 350 feet (Compiled by Erling Dorf)

Appendix A.3

Mesozoic Stratigraphic Section
Bighorn Basin—Beartooth Mountains, Wyoming-Montana

(Parsons, 1978)



	(Fort Union: Polecat Bench fm–Paleocene).	
CRETACEOUS	Lance fm.	Gray to greenish-gray shales interbedded with grayish-buff sandstones and occasional coal beds.
	Lennep ss.	Brownish thinly-bedded ss; some sh.
	Bearpaw sh. (Meeteetse)	Dark gray soft shales with numerous zones of fossiliferous calcareous concretions.
	Judith River fm.	Light-colored sandstones, interbedded with sandy shales and siltstones, and occasional dark gray shales.
	Claggett sh.	Dark gray soft shales, with some zones of concretions, and with more sandy beds toward top.
	Eagle ss.	Massive light gray sandstones at base grading upward into thinly-bedded ss, sh, and occasional coal beds.
	Telegraph Creek fm.	Thinly-bedded grayish shales and sandstones.
	Cody sh.	Light to dark gray soft shales in lower part to brownish or olive shales and thin platy sandstones in upper part; more sandy shales near top; interbedded calcareous concretionary zones
	Frontier fm.	Massive grayish sandstones interbedded with thinly-bedded ss and sh.
	Mowry sh.	Brownish to gray hard shales, sandy in lower part; interbedded bentonite beds.
	Thermopolis sh.	Dark gray soft shales interbedded with numerous bentonite beds; 20-foot sandstone unit in lower part.
	Cloverly fm.	Basal conglomerates or pebbly ss; reddish sh in middle; grayish ss at top.
Jurassic	Morrison fm.	Variegated reddish, purplish, and gray sh interbedded with light gray ss.
	Sundance fm.	Basal brownish limestones at base, calc sh in middle, greenish sh & ss at top.
Triassic	Gypsum Spr fm.	Thin lms, reddish sh and gypsum.
	Chugwater fm.	Typical red-beds: shales, siltstones and sandstones.
	(Phosphoria formation–Permian.)	

Vertical scale: 1 inch = approximately 1,000 feet (Compiled by Erling Dorf)

Appendix A.4 (Parsons 1978)

Cenozoic History and Stratigraphy—Absaroka-Yellowstone Volcanic Provinces

Epoch	Cycle	Events and stratigraphy
		Minor faulting—Recent. Pinedale glaciation—Late Wisconsin. Erosion and minor faulting
PLEISTOCENE	3rd volcanic cycle	*Plateau Flows*—rhyolites; at least 1,500m, filled the calderas. Dated from 560,000 to 70,000 years on K/Ar by U.S.G.S. The Obsidian Cliff Flow is one of these; dates at 75,000 years. *Osprey Basalts* and gravels: post canyon cutting; late in Plateau flow time Canyon cutting cycle; correlates with Yarmouth interglacial. *Swan Lake Flat Basalts*—Sheepeaters Cliffs; before erosion. Early Plateau. *Lava Creek Tuff* of *Yellowstone Group* (0.6 m.y., 300m thick, Near age of Kansan Glaciation. Yellowstone Caldera formed by collapse of magma-chamber roof after eruption. *Undine Falls Basalt.* 6m thick. *Mt. Jackson Rhyolite Flows:* 2 major flows, 400m at type section. 0.6 to 0.8 m.y.
PLEISTOCENE	2nd	*Mesa Falls Tuff* of *Yellowstone Group* (1.2 m.y.) Associated with the Island Park Caldera in Idaho.
PLEISTOCENE	1st cycle	Sediments and *basalts* of the *Narrows* at Tower Falls; fills late Pliocene valley, gravels have about 10% of rhyolite welded tuff clasts. *Huckleberry Ridge Tuff (Yellowstone group):* 2 m.y. 170m at type locality. Major caldera in central to southwest Yellowstone, now partly filled. Local Late Pliocene basalts: *Junction Butte Basalt, Overhanging Cliff Basalt.* prepaleovalley at Tower, underlying gravels have no rhyolite clasts.
		Long erosion: regional uplift and deformation, intermittent local eruptive activity (great amounts in Jackson Hole). Oligo. thru Pliocene.
EOCENE	Absaroka Volcanic Super-Group	*Wiggins, Tepee Trail, Two Ocean, Langford fms* of *Thorofare Creek Group* (2,000m, 44-48 m.y.), Volcaniclastics and andesite lavas. *Late Acid* and *Basic Breccias* of Hague. *Mt. Wallace, Wapiti fms., Trout Peak Trachyandesite* of *Sunlight Group.* Volcaniclastics, flows (3,000m, 48 m.y.). *Early Basic Breccia* and *Early Basalt Flows* of Hague. *Sepulcher, Cathedral Cliffs, Lamar River fms.* of *Washburn Group.* (1,000m, 49 m.y.), Volcaniclastics, lavas. Early Acid and Basic Breccias of Hague.
EOCENE		Willwood Formation in Bighorn Basin and Shoshone River areas (Early Eocene); Crandall conglomerate, local stream channel deposits in Clarks Fork Valley and Sunlight Basin. Fort Union Formation—Paleocene.

Geologic Timescale (Fritz, 1996)

AGE	ERA	PERIOD	EPOCH	Representative formation Names of rocks exposed in the Yellowstone Country
.01	Cenozoic	Quaternary	Recent	Hot springs, landslides, stream, glacial, lake deposits
1.6	Cenozoic	Quaternary	Pleistocene	Rhyolite, welded ash, basalt of 2nd & 3rd volcanic cycles
5	Cenozoic	Tertiary	Pliocene	Huckleberry Ridge Tuff of 1st volcanic cycle
24	Cenozoic	Tertiary	Miocene	Six Mile Creek Formation
27	Cenozoic	Tertiary	Oligocene	Renova Formation
58	Cenozoic	Tertiary	Eocene	Absaroka Volcanic Supergroup Willwood Formation
66	Cenozoic	Tertiary	Paleocene	Fort Union Formation
144	Mesozoic	Cretaceous		Everts Formation Eagle sandstone, Telegraph Creek Formation, Cody Shale Various sands and shales near Cody
208	Mesozoic	Jurassic		Morrison Formation Ellis Group
245	Mesozoic	Triassic		Gypsum Springs Formation Chugwater Formation
286	Paleozoic	Permian		Phosphoria Formation
320	Paleozoic	Pennsylvanian		Tensleep/Quadrant Sandstone Amsden Formation
360	Paleozoic	Mississippian		Madison Group
408	Paleozoic	Devonian		Three Forks Shale Jefferson Dolomite
438	Paleozoic	Silurian		No rocks in Yellowstone Country
505	Paleozoic	Ordovician		Bighorn Dolomite
570	Paleozoic	Cambrian		Snowy Range Formation Pilgrim Limestone Park Shale Meagher Limestone Wolsey Shale Flathead Sandstone
4700	Precambrian			Granite, gneiss, schist, amphibolite gabbro dikes, pegmetite of crystalline basement

Geologic History of Yellowstone

Zibi Turtle

In the Archean Era the area that we now call Wyoming was a part of what is called the Wyoming province. This province was one of seven Archean provinces that accreted in the Proterozoic and make up the present North American craton. Whether these provinces were originally microcontinents or whether they began as one continent that was rifted and reaccreted is not known (Snoke, 1993). This Archean basement forms the cores of mountains uplifted during the Laramide orogeny. In the northern and northwestern parts of Yellowstone National Park erosion has exposed 2.7 Ga granite plutons and granitic gneisses intruded by a somewhat younger diabase.

Most of the subsequent history of the Yellowstone region involves erosion and deposition as oceans transgressed and regressed across the region. In the Paleozoic Era (570 - 245 Ma) Wyoming was on the western shore of continent. A variety of sedimentary rocks (limestone, dolomites, shales, sandstones) was deposited under the changing marine environment. In the Mesozoic Era (245 - 65 Ma) sea level was quite high and the center of the continent flooded. Marine and non-marine sedimentary rocks were deposited as the ocean transgressed and regressed from the east. During this time the Farallon plate was subducting under the western margin of the continent generating volcanic activity consistent with steep-dipping subduction.

In the late Cretaceous and into the early Tertiary period, roughly between 75 and 45 Ma (ending perhaps as early as 51 Ma in Wyoming), huge mountains were built by the Laramide orogeny. As uplift occurred the ocean retreated for the last time. Also during this time the volcanic activity migrated eastward perhaps due to shallow-dipping or "flat-slab" subduction. The Gallatin range to the northwest of Yellowstone was active from ~53 to ~49 Ma. The Absaroka volcanic field was active from ~49 to ~44 Ma. The field has two lines of volcanoes the eastern belt being older than the western. Two theories have been developed to explain the inland location of these ranges: 1) they formed a magmatic arc above a shallow-dipping subduction zone, and 2) they were formed by back-arc rifting behind a steeper subduction zone. In the late stages of the Laramide orogeny or soon afterward faulting occurred on the Heart Mountain detachment.

Following the Laramide mountain building extensive erosion occurred depositing sediments in southeastern Wyoming.

The most recent cycle of volcanism at Yellowstone may be the result of a hot spot (although a number of other theories have also been developed Smith and Braile, 1993). The earliest volcanic rocks associated with this hotspot are in the Snake River plain and date to ~16 Ma. A series of calderas extends between the 16 Ma caldera and Yellowstone, getting progressively younger along the track to the northeast. This series is consistent with a plate velocity of 3-5 cm/yr relative to the hotspot, although the situation is complicated by periods of crustal extension. The Yellowstone volcanic field became active at ~2.5. The eruptive cycles include initial eruptions of basaltic and rhyolitic lavas followed by explosive caldera forming eruptions which generated immense deposits of tuff. Finally more magma is extruded along the faults at the edges of the caldera. Three of these cycles have occurred in Yellowstone resulting in caldera forming events at 2.0, 1.3, and 0.6 Ma. A smaller event created the caldera that forms the West Thumb of Yellowstone Lake at 0.15 Ma. The youngest rhyolite flows in Yellowstone are between 0.08 and 0.07 Ma old.

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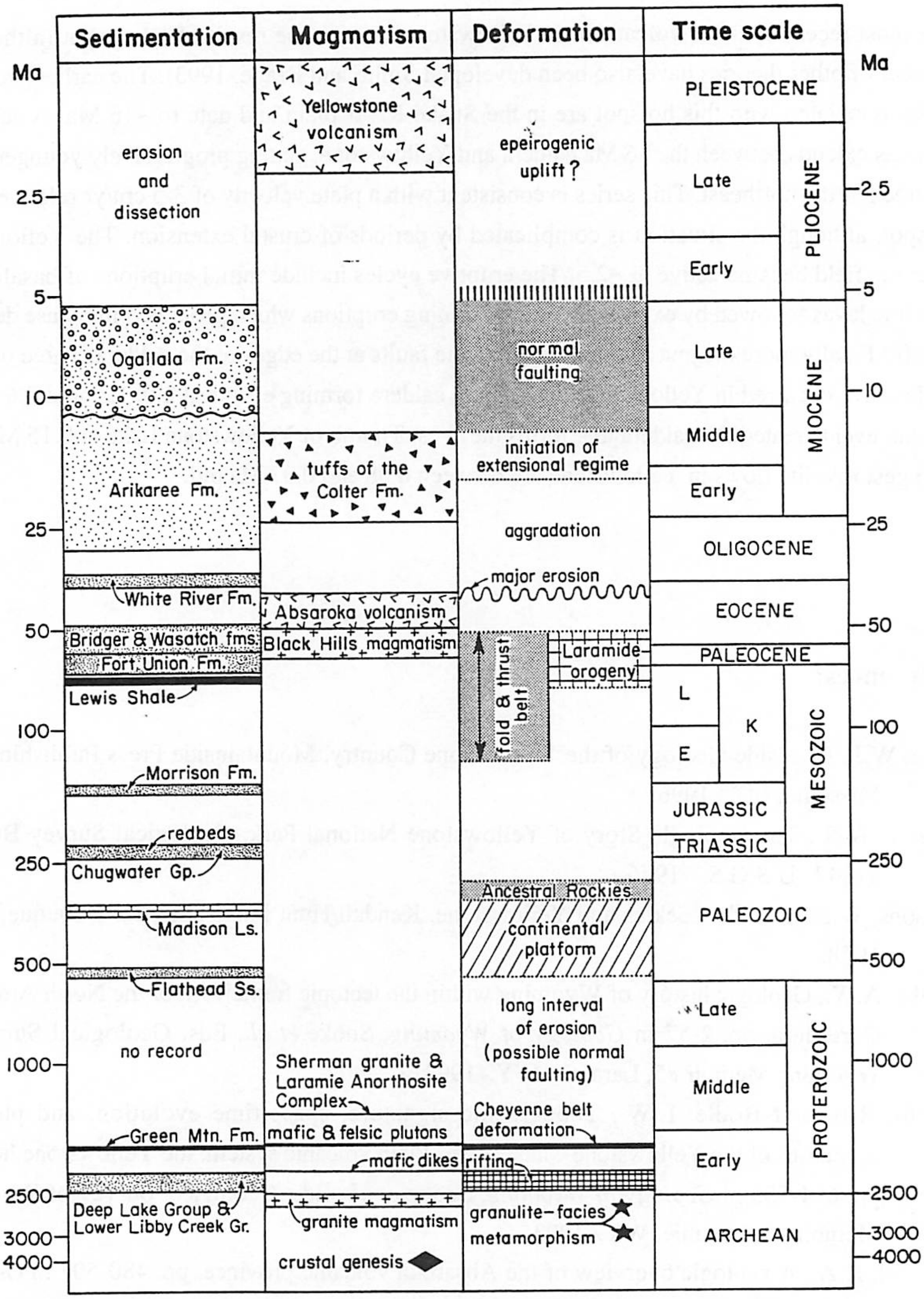
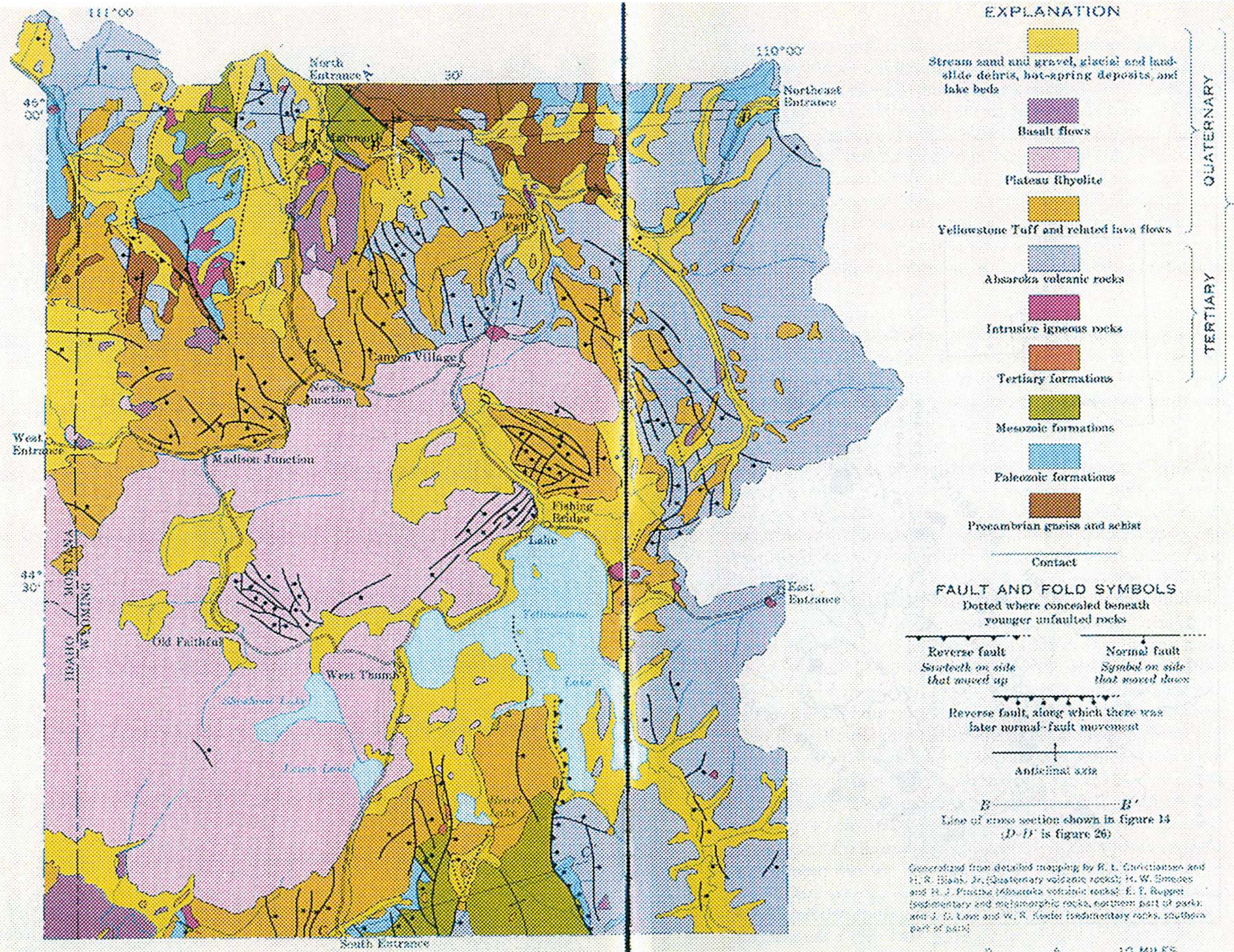


Figure 3. Salient aspects of the geologic history of Wyoming, including sedimentation, magmatism, and deformation. Only selected stratigraphic units are delineated in the sedimentation column. Logarithmic time scale in Ma; geologic time scale after Palmer (1983). This diagram was designed after Dickinson (1991, figure 5). The age range of Late Archean granitic rocks is derived from Peterman and Hildreth (1978) and Stuckless and others (1985). The age range of the Colter Formation and initiation of normal faulting is from Barnosky (1984). Other dates are derived from various publications cited in the text.

(Snoke, 1993)



GEOLOGIC MAP OF YELLOWSTONE NATIONAL PARK (PLATE 1)

(Keeter, 1976)

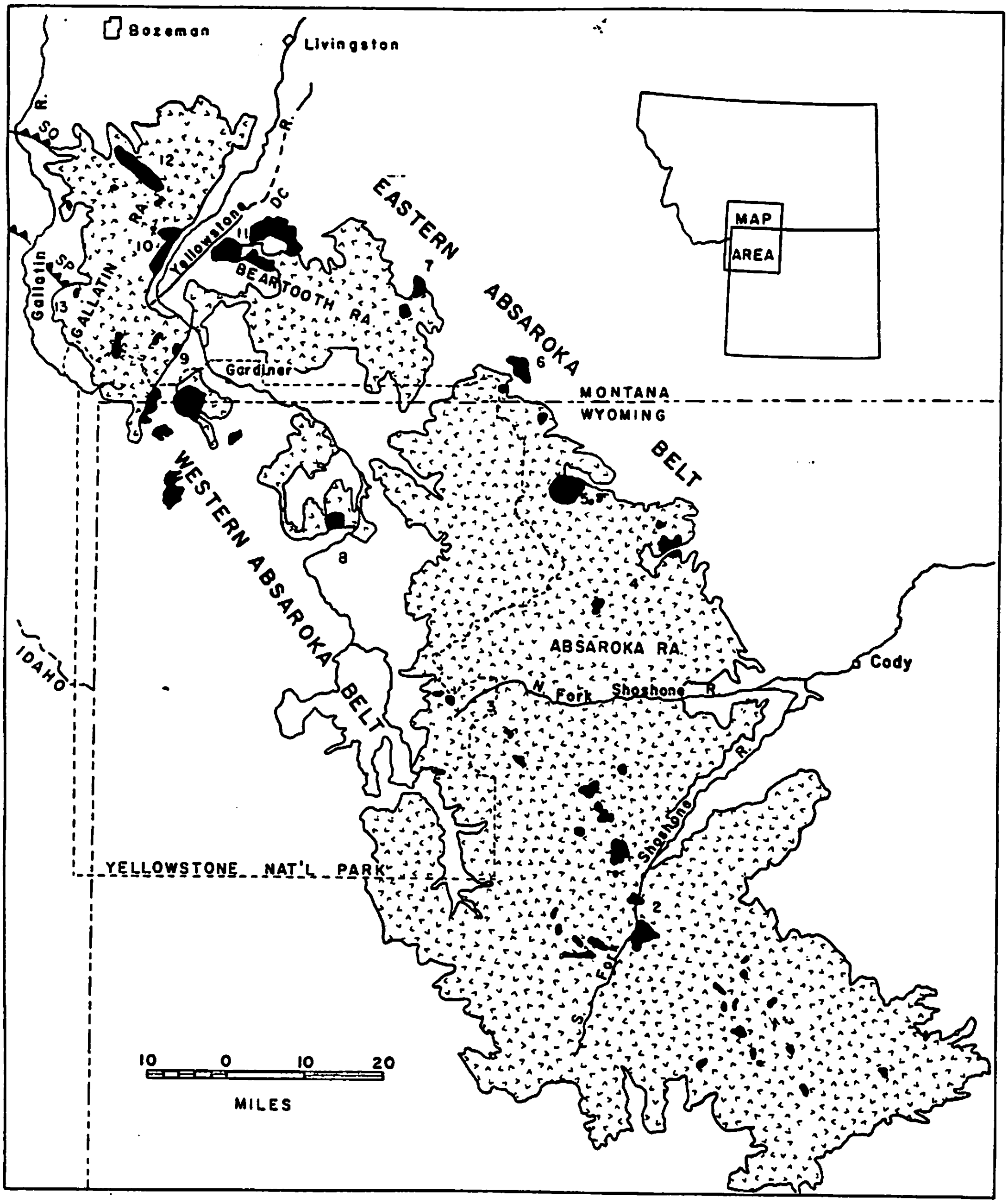


Figure 2.6. Geologic map of the Absaroka-Gallatin Volcanic Field. (Chadwick, R. A., 1970, Geol. Soc. America Bull., p. 268). V pattern = Eocene-Oligocene volcanics; black = principal vent complexes and intrusives in and between eruptive centers. Principal recognized eruptive centers are aligned along two subparallel belts and are numbered as follows: *Eastern Absaroka belt:* (4) Sunlight; (5) Hurricane Mesa; (6) Cooke City; (7) Independence; (10) Point of Rocks; (11) Emigrant Peak; (12) Northern Gallatin Range dike swarm. *Western Absaroka belt:* (1) Kirwin; (2) Ishawooa; (3) Sylvan Pass; (8) Mt. Washburn; (9) Electric Peak; (13) Porcupine Creek.

(Parsons, 1978)

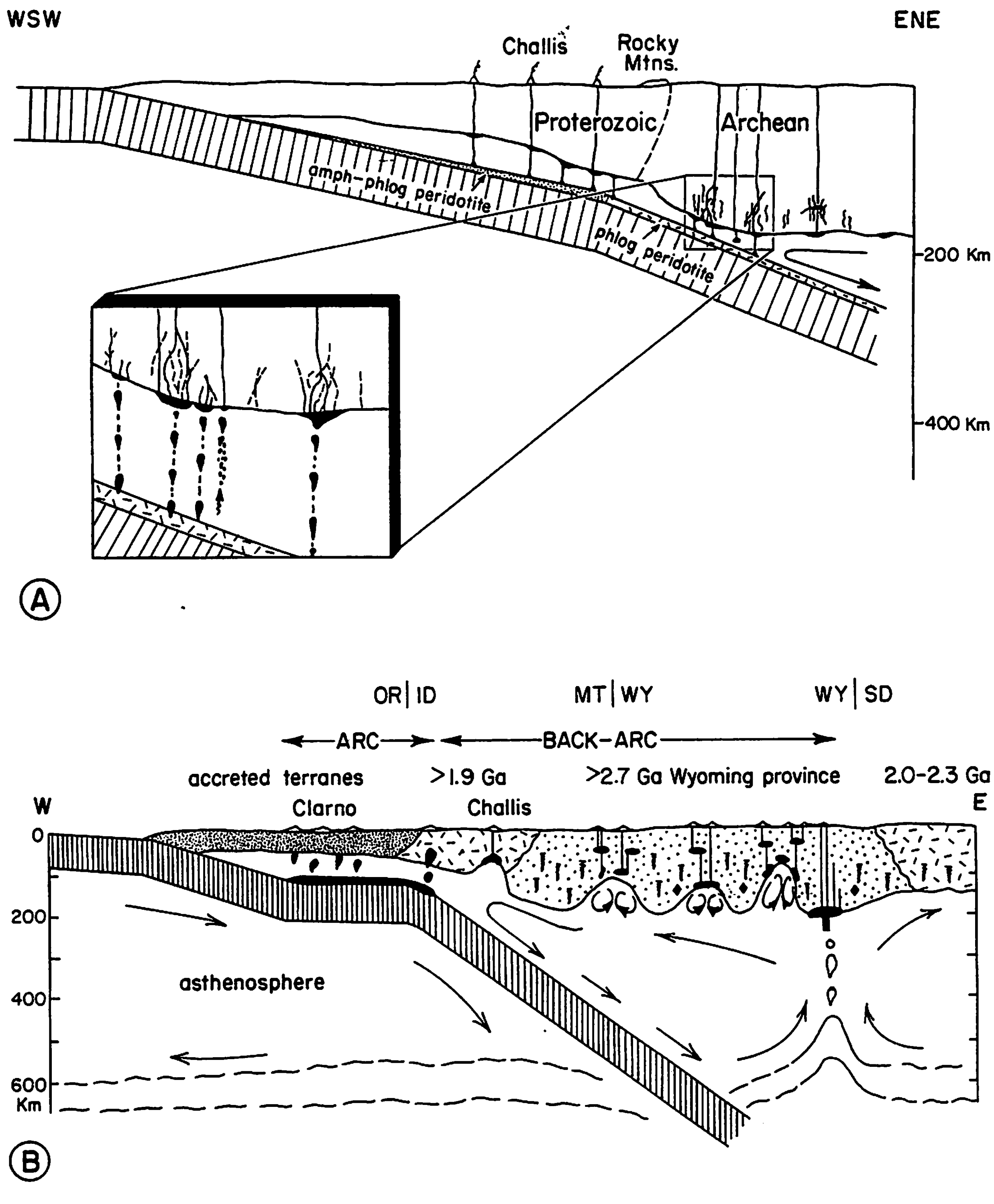


Figure 12. Contrasting petrogenetic models for Paleogene magmatism within the Wyoming province: (A) subduction-related arc magmatism associated with partial melting of asthenospheric mantle triggered by the infiltration of melts released from a metasomatized carapace formed above the low-angle slab of Farallon Plate lithosphere (after O'Brien and others, 1991); and (B) back-arc magmatism associated with asthenospheric upwelling (after Eggler and others, 1988). Some details and criticisms of these models are discussed in the text.

(Snoke, 1993)

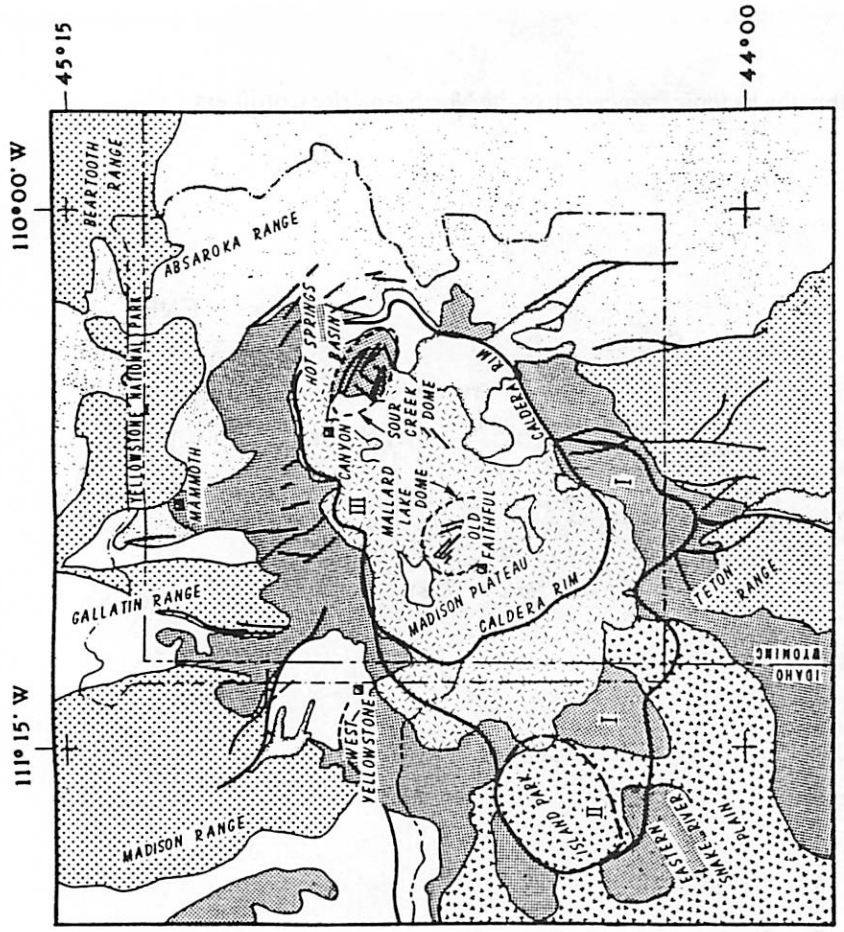


Figure 11. Geologic map of the Yellowstone Plateau showing the locations of Yellowstone calderas, Quaternary volcanic flows, and late Cenozoic normal faults (modified from Christiansen, 1984). Yellowstone calderas are shown by age: I = 2.0 Ma, II = 1.2 Ma, and III = 0.6 Ma.

(Smith and Braile, 1993)

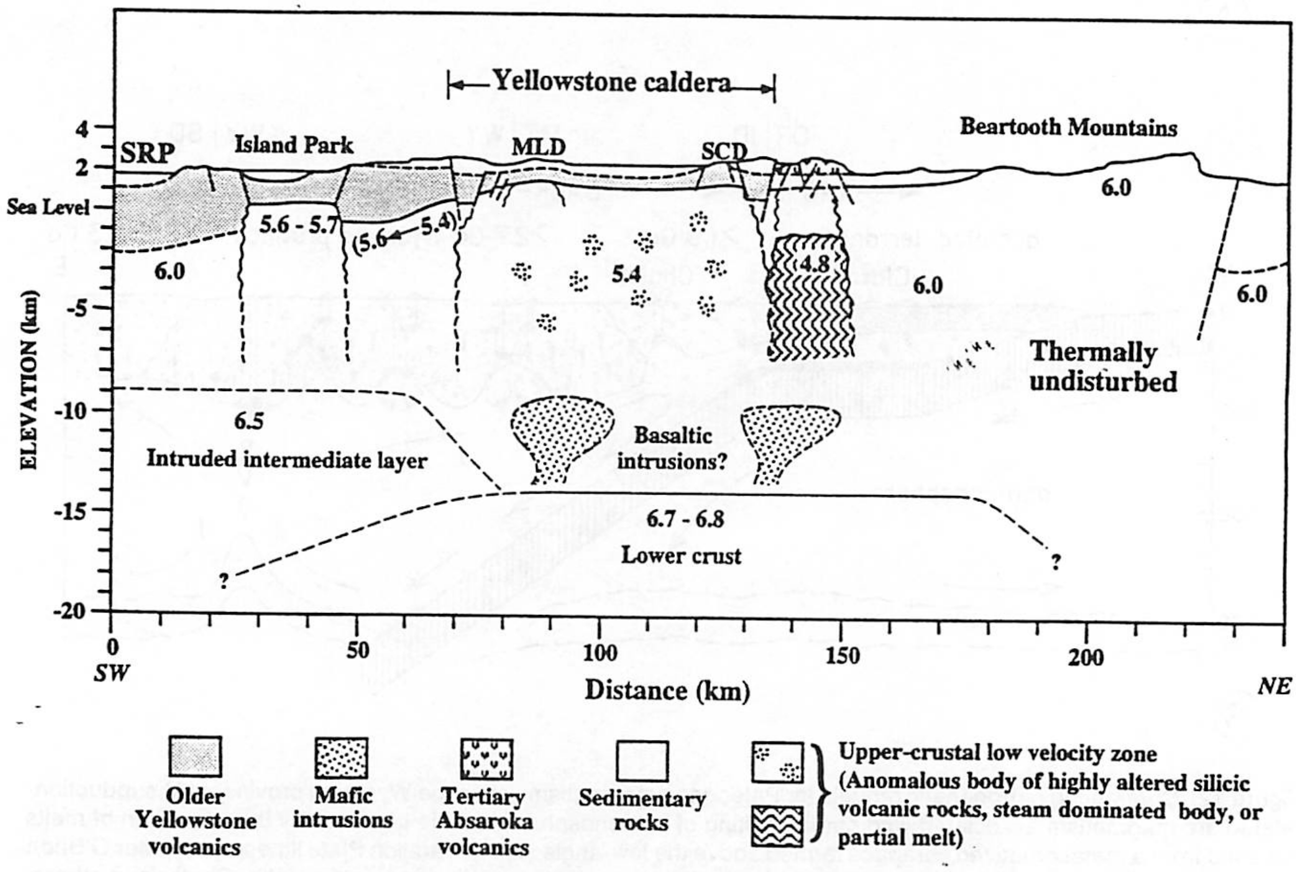


Figure 22. Cross section (northwest-southeast) of the upper-crustal P-wave velocity structure of the Yellowstone Plateau; numbers are km/s (from Brokaw, 1985). Interpretation based upon two-dimensional ray trace modeling of data from the 1978 and 1980 YSRP seismic experiments. MLD = Mallard Lake dome and SCD = Sour Creek dome.

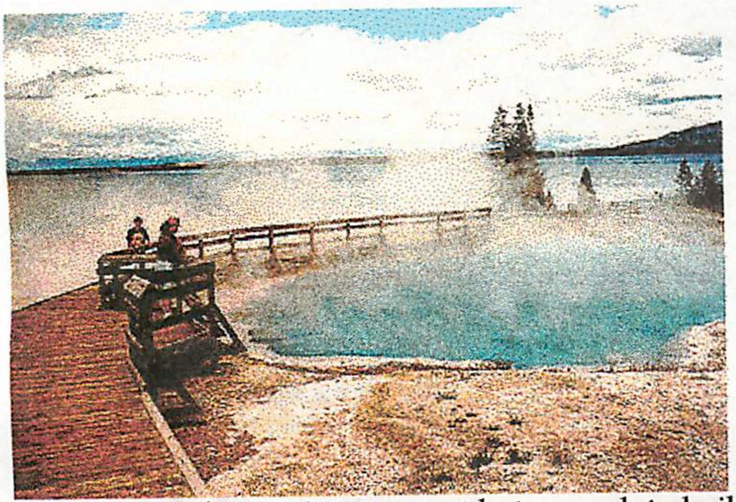
(Smith and Braile, 1993)

Hydrothermal Features

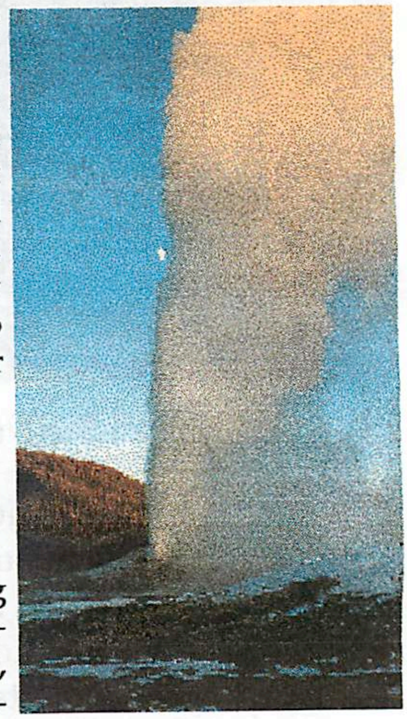
As spouted by Barbara Cohen

Yellowstone National Park contains the greatest number of geysers and hydrothermal features in the world. Approximately 400 of the world's 700 geysers are located in nine geyser basins within the park. Old Faithful is probably the most famous geyser, but Steamboat Geyser in Norris Basin is currently the world's tallest. Major eruptions of Steamboat Geyser can be over 350 feet tall. These features are the result of the Yellowstone hot spot where the earth's crust is extremely thin and magma lies close to the surface (about 2 miles deep). Water from heavy precipitation in the area seeps down through the ground, gets heated, and eventually returns to the surface as a geyser, hot spring, pool, mud pot, or other hydrothermal feature.

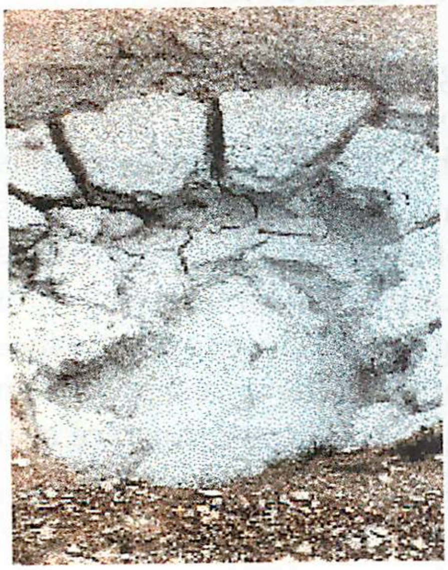
Glossary



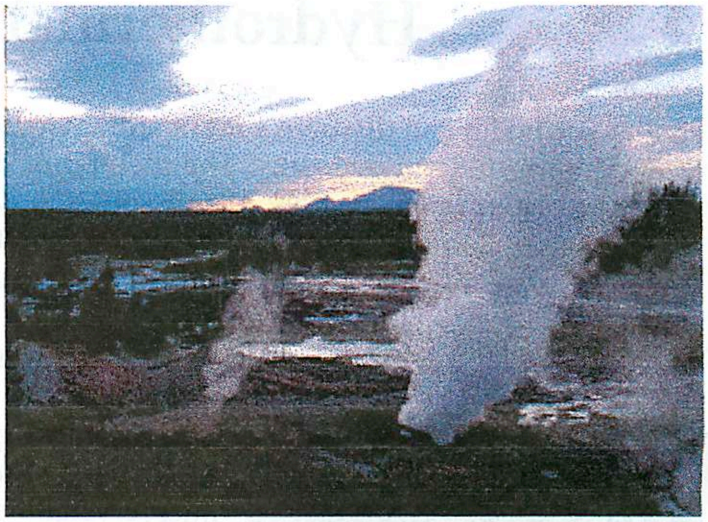
A *hot spring* is any pool or discharge of hot water onto the surface. Geysers and mud pots are specific kinds of hot springs. Two things are needed to produce hot springs: an underground heat source, and an abundant supply of meteoric water. The water seeps underground, is heated, and rises back up to the surface. Water can be heated well above the boiling point if it is far underground and under the pressure of overlying water. Some hot springs are not hot enough to boil but may have that appearance when gases bubble through them. Hot springs are found in many, many places on the earth, and are often used as natural spas.



A *geyser* is a hot spring that throws water into the air, either perpetually or periodically. In addition to a heat source and an abundant supply of water, geysers require a special plumbing system. In a normal hot spring, water and steam can rise unrestricted. If there is a constriction in the conduit to the surface, however, steam bubbles may build up and block the way. The steam may break though all at once, pushing the overlying water up and out. This suddenly reduces the water overpressure, causing the water below to flash to steam and catastrophically force the rest of the water and steam out of the pipeline.

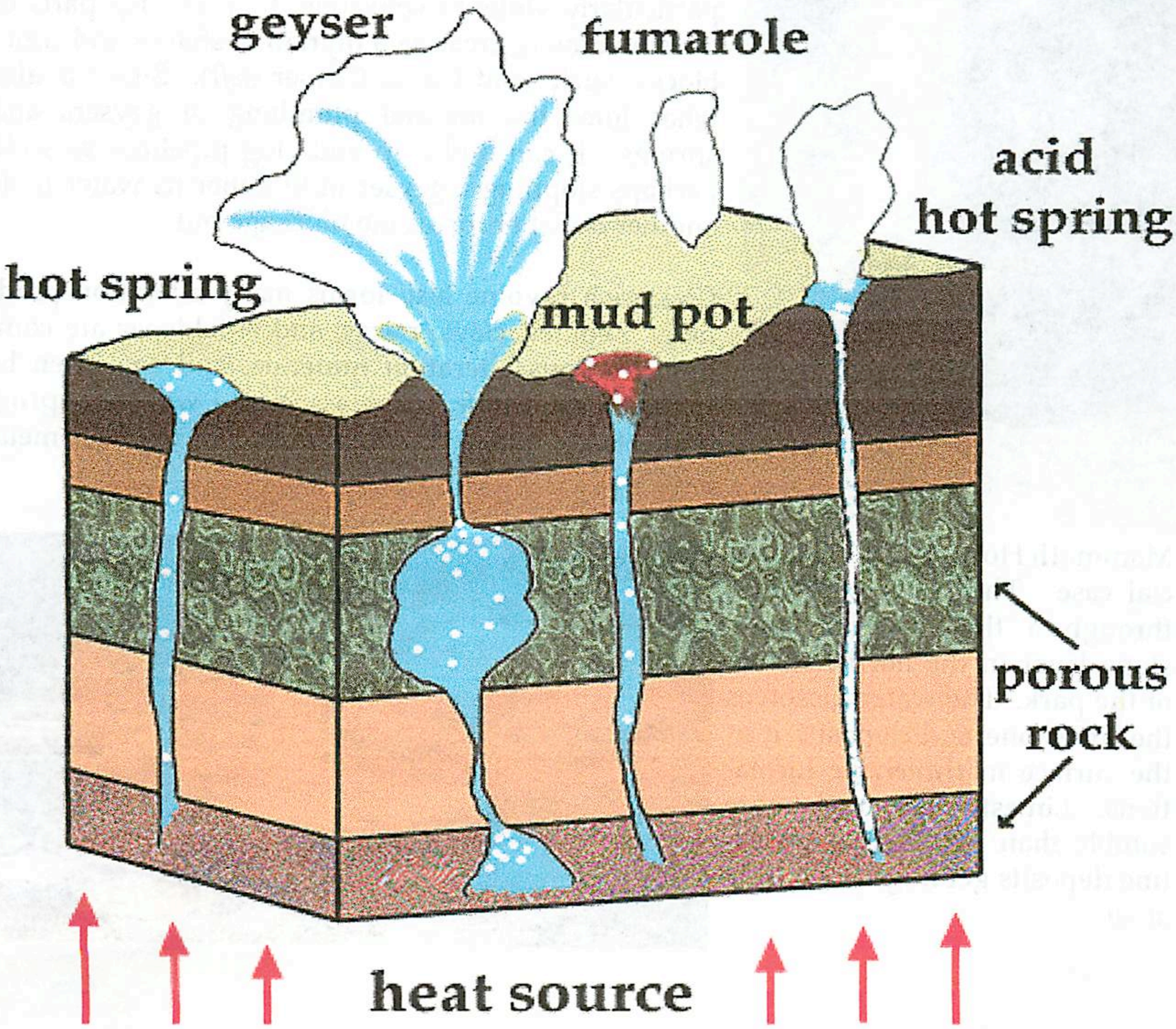


A *mud pot* is a hot spring that doesn't have an abundant water discharge. Hot, acidic water works to dissolve the surrounding rock and bring material to the surface. If there is a large discharge rate, the dissolved constituents are lost. If there is not a lot of water, the water pool with become muddy with particles of altered rock in suspension. Oxides of iron, aluminum, and manganese commonly color these pools, giving them the name *paint pot*.



A *fumarole* is a vent which discharges primarily steam. The conduit above a boiling water source may not be sealed enough to conduct water, and so only the steam will escape. Fumaroles are most visible when cooler air condenses the issuing steam. Fumaroles also release magmatic gases like CO_2 and H_2S.

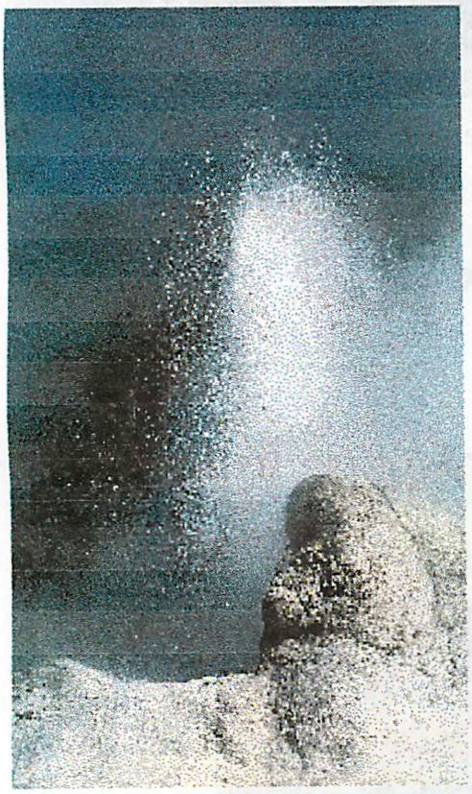
Acid hot springs are fumaroles capped with pools of water. If hot steam and gases escaping from the magmatic heat source bubble through water, they will heat and acidify the water. The system below an acid hot spring is vapor-dominated, not liquid-dominated.



Hydrothermal deposits

Hot, acidic water can dissolve a lot of stuff. Geyser and hot spring fields are commonly covered with mineral deposits. The method of dissolution and redeposition is akin to what goes on in caves, namely, gas dissolves in water, creating an acid, which then eats out the rock. At the surface, the gas exsolves and the minerals precipitate out. The gases originate in the magma body which heats the system.

Carbonic Acid: $CO_2 + H_2O \Rightarrow H_2CO_3$ Sulfuric Acid: $H_2S + 4H_2O \Rightarrow H_2SO_4 + 4H_2$



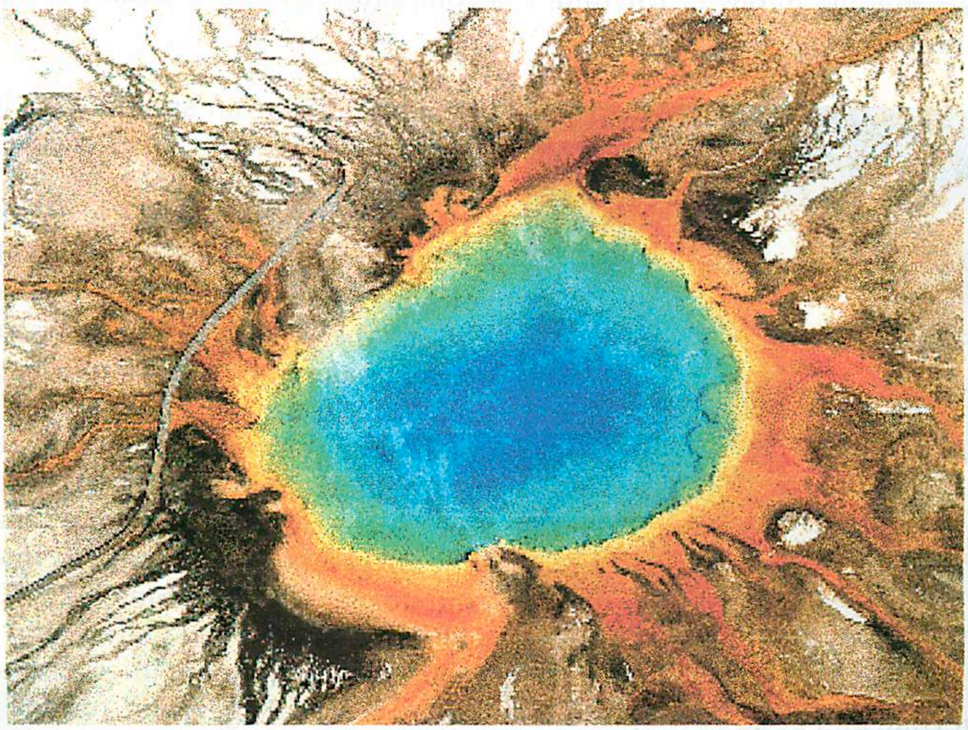
Because most geysers are in rhyolite fields, deposits are mainly ***siliceous sinter***. Sinter is amorphous or microcrystalline silica, similar to opal or chalcedony. Sinter can be left in sheets as water floods over a plain, or be built up around a vent. If the geyser has been behaving well, a nice cone forms. If the geyser has particularly violent explosions, they can rip parts of the sinter away, creating a myriad of shapes and sinter blocks, such as at Castle Geyser (*left*). Sinter is also what lines the internal plumbing of geysers and springs. It can build up and clog pipelines as well, perhaps stopping a geyser until either its water finds another outlet or forces the blockage out.

Glass-rich rhyolite also forms many alteration products. Zeolites, clays, micas, and K-feldspar are common hydrous alteration minerals, and can often be found in mud pots. Also associated with hot spring deposits are quartz, calcite, fluorite, pyrite, and metal oxides.

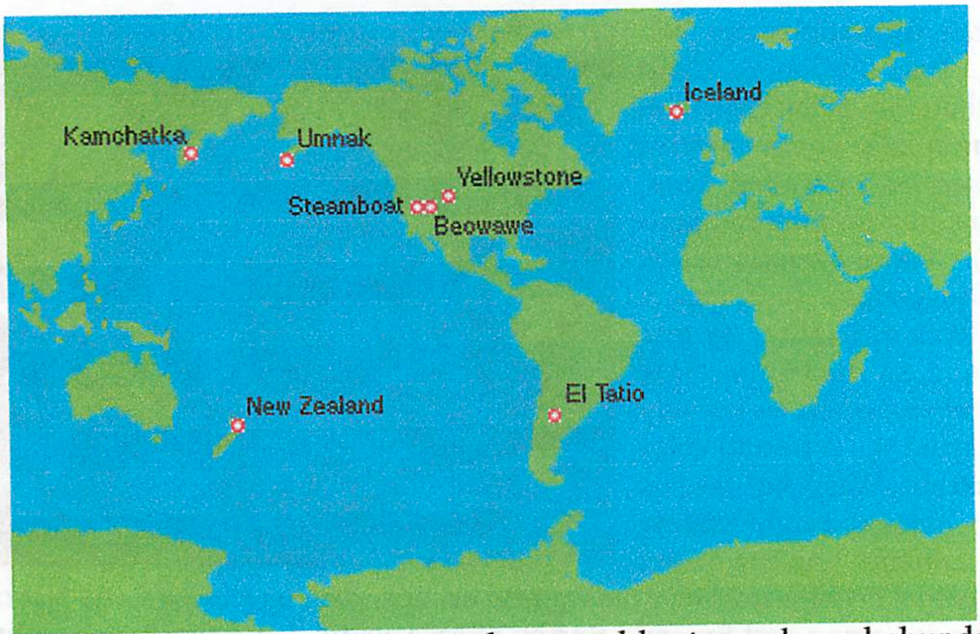
Mammoth Hot Springs are a special case. The water percolates through a thick marine limestone layer in the northern part of the park. The water dissolves the limestone and deposits it at the surface in ***travertine*** formations. Limestone is much more soluble than rhyolite, so travertine deposits get huge in no time at all.

Color

While some formations are colored by trace minerals and oxides, others sport brightly-colored thermophilic *cyanobacteria* (which used to be called blue-green algae, but isn't really plant-like at all). These bacteria thrive in hot, acidic waters. Each strain, however, lives in a rather narrow thermal zone, so the temperature of the water can often be crudely estimated from the type and color of the bacteria. Very hot waters (70-100°C) support bright yellow and pink colonies. As the water cools, the colors become darker, grading into orange, rust, and brown. At Norris Geyser Basin, Echinus Spring and Emerald Spring release acidic water that breeds a lime-green strain. Orangish bacteria color the runoff channels from Porcelain Basin. Perhaps the most spectacular example of color from bacteria, as well as thermal zoning, is found at Grand Prismatic Spring (*below*). Here, the spring vent is located at the center of a large pool. The temperature of the water cools off toward the edges of the pool. Each thermal zone is occupied by a different strain of bacteria. This is a true-color image!!



World Geyser Fields



Many areas around the world have an underground heat supply and abundant water, thus producing hot springs. To have a geyser, though, the conduit bringing water up to the surface must be water- and pressure-tight. This is best accomplished by sealing the pipeline with mineral deposits. It turns out that sealing isn't so easy. To seal a pipeline, the water must be quite rich in silica, and this is only found where the hot springs flow though a silica-rich rock like rhyolite. In fact, more than 95% of the world's geysers are located in a rhyolite deposit. Rhyolite is a comparatively rare volcanic rock, so geyser fields are rare.

The namesake of all spouters is Geysir (*left*), located in Iceland. Geysir means "gusher." Iceland sports about a dozen very small geyser fields. El Tatio in Chile is located in a valley high in the Andes surrounded by active volcanoes, and contains more than 60 geysers. Within the Valley of Geysers in Siberia, approximately two hundred geysers are known, and are unusual in that they often spout at angles. About a dozen geysers exist in a remote field on the Aleutian Islands. New Zealand has used its more than 200 geysers for geothermal energy, so that only several dozen remain. Small geyser fields in California and Nevada have been completely destroyed by human intervention. Crystal Geyser in Utah and Soda Springs in Idaho are examples of "geysers" formed by drilling.

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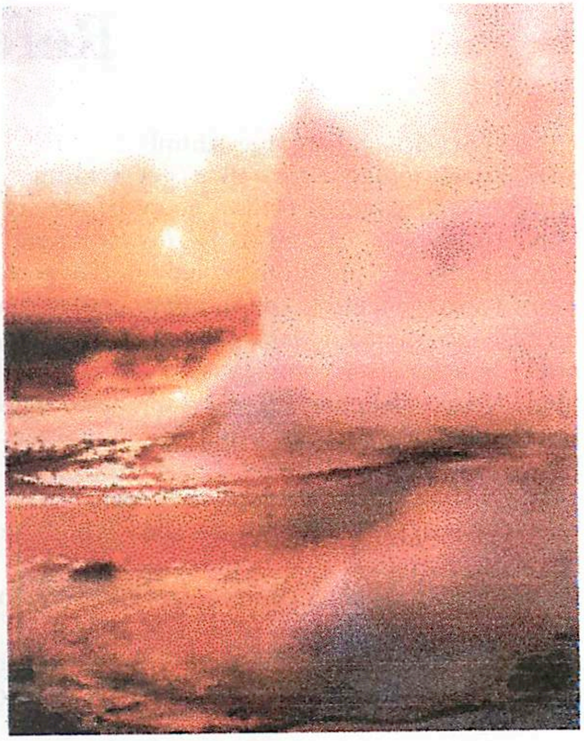
The Legend of the Geysers



Long, long ago, the peaceful Ashochimi Indian tribe inhabited a rich and luxuriant valley on both sides of a river, now known as the Russian River north of San Francisco. With ample hunting and fishing, with crops of wild clover, wild oats, acorns, roots, and berries, they lived a happy and contented life of abundance--until Spaniards and Mexicans arrived, establishing their settlements. The Ashochimis were compelled to hunt for adequate game farther and farther away from their homeland, because their traditional hunting grounds were overtaken by the intruders.

One day, Guavo and Kolo, two young Ashochimi hunters, caught sight of an unusually large grizzly bear. They shot their barbed arrows into the monstrous animal's side. The bear dropped instantly as if dead. But the hunters knew the tricks of the grizzly, that he would fall to the ground at the slightest wound, pretending he was dead.

Again the young hunters fired their flint-headed arrows and struck the bear. With four arrows in him, the grizzly got to his feet and staggered into the underbrush, leaving a trail of blood. Guavo and Kolo pursued at a safe distance, with their arrows ready. They knew it would be only a matter of time until they could claim their prize.

Up the canyon, the grizzly bear led the two young hunters, pausing occasionally to rest. Guavo and Kolo were amazed at its strength, as mile after mile the bear struggled on, never wavering from its direct course through the canyon.

Most of the way was timbered with low chaparral, but, suddenly, ahead the hunters saw an open grassy spot where the grizzly bear came to a halt. To Guavo and Kolo the animal seemed to writhe in pain. They let out a victory whoop at the sight of their dying quarry. But the startled grizzly bear gave forth one more life-effort as he plunged forward into a ravine below.

Guavo and Kolo ran to the edge of the cliff, where they saw the lifeless body of the grizzly at the bottom of the gorge. At first in their excitement, they did not notice hundreds of minute jets of steam coming out of the hillside. They did not at first hear the hoarse rushing sound that filled the canyon with a continuous noise.

Guavo and Kolo ran to the dead grizzly. They halted in amazement when they suddenly realized they were on the brink of a "witches' cauldron" in the midst of seething steam spouts. They wondered if the geysers had been there before the grizzly bear died.

They took one horrified look at the steaming hillsides, they took one breath of the sulphurous vapor, they took one terrified glance at the trembling earth beneath them. Scared, Guavo and Kolo ran as fast as they could back to their village.

Chief Asho and his council listened sceptically as the two young hunters told their story:

"After the grizzly bear died, the ground began to smoke," said Guavo.

"Water boiled and bubbled without fire," said Kolo.

"Everywhere steam came out of holes in the ground," said Guavo.

"Choking smells came from the steam," said Kolo.

"Where we stood, the ground shook and trembled," said Guavo.

Because the two young hunters were known among their tribe to be truthful, Chief Asho said, "Take twenty young braves with you and show them the way to the place you have told us about."

All was true. There lay the dead grizzly bear beside the black, bubbling, steaming water.

"The grizzly's evil spirit brought forth the strange hot steam to heal his wounds," declared the tribal Medicine Man. "Before he died, the bear must have known this to be his healing place."

They skinned the bear and cut up parts of the meat for all of the braves to carry back to their tribe. Guavo and Kolo were awarded the skin as their prize, and the tribe prepared a huge fire to roast the bear meat for a feast.

Medicine Man thought the healing steam jets might help their sick people. He led the tribal men and built platforms over the steaming area, then placed their invalids upon them. But that night, strange sounds arose in the darkness and the earth trembled violently. Medicine Man remembered stories of evil spirits within grizzly bears, and became concerned that those evil spirits were trying to take charge of the geysers.

"All is not good," he warned his people. "Go back to your village and stay there."

Soon thereafter, a strange plague appeared among the tribal men.

"We must help the sick and dying," said Medicine Man. "But I am afraid for you to return to the medicinal springs, because the angry bear's spirit has caused this pestilence."

Finally, a gray-haired, beloved Ashochimi sculptor appeared before Chief Asho.

"With my special tools, I can carve a stone guardian high above the canyon, whose good spirit will appease any angry spirits below," he said as he pleaded for permission.

"Go ahead. We anxiously await the completion of your stone guardian," replied Chief Asho.

Day after day the old sculptor worked alone. He chiselled at the hard rock until it resembled a human face. Each day he carved from dawn until the light of day was nearly gone. The people watched from a distance, eagerly awaiting the time when they could return for healing at the geysers.

"Only one more day of work on the rocky head," announced the old sculptor. But that evening he did not return to the village. A terrible earthquake occurred, toppling many cliffs, and it continued shaking throughout the night.

When the sun arose the next morning, the old sculptor had disappeared; however, the stone face on the great rock was finished and stood alone above the geysers. New springs jetted forth everywhere farther down the river. Medicine Man led the men of the tribe to examine the new springs.

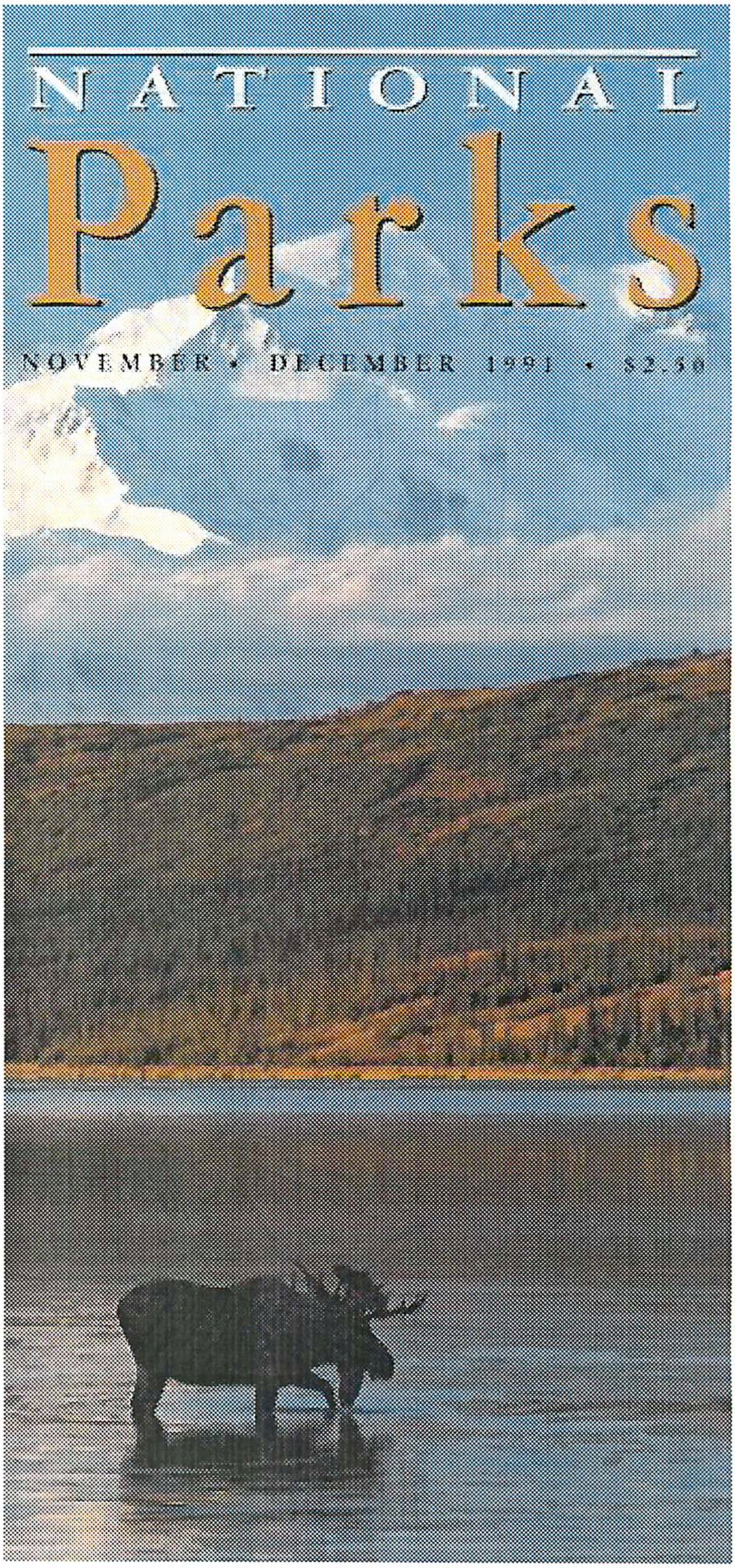
"It is safe now," Medicine Man announced bowing reverently toward the stone guardian of the canyon. "Let us build new platforms of willow boughs and bring the sick."

This they did. Steam vapors encircled and healed the invalids of the Ashochimi tribe miraculously. All the people rejoiced at the blessing of good health.

There above them, they were always mindful of the sculptured stone face that guarded all Indians from the wrathful spirit of the dead grizzly bear. They also were mindful of their loving sculptor who gave his life in sacrifice. Guavo and Kolo were accorded special places of honor among the young braves of their tribe for their discovery of the geysers.

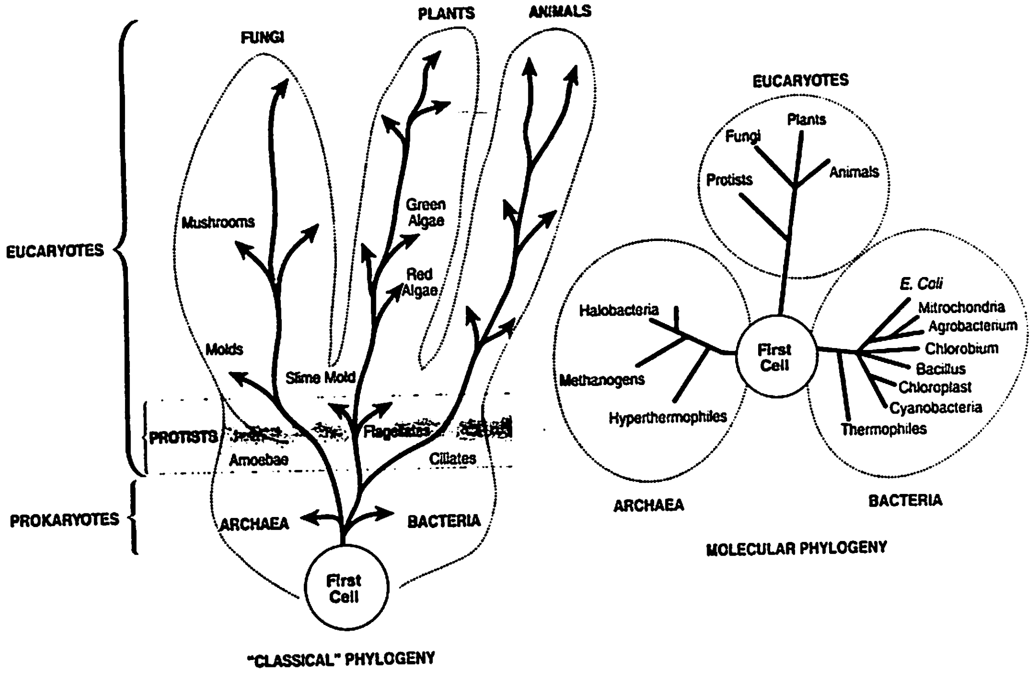
in extreme environments

(trilling!)

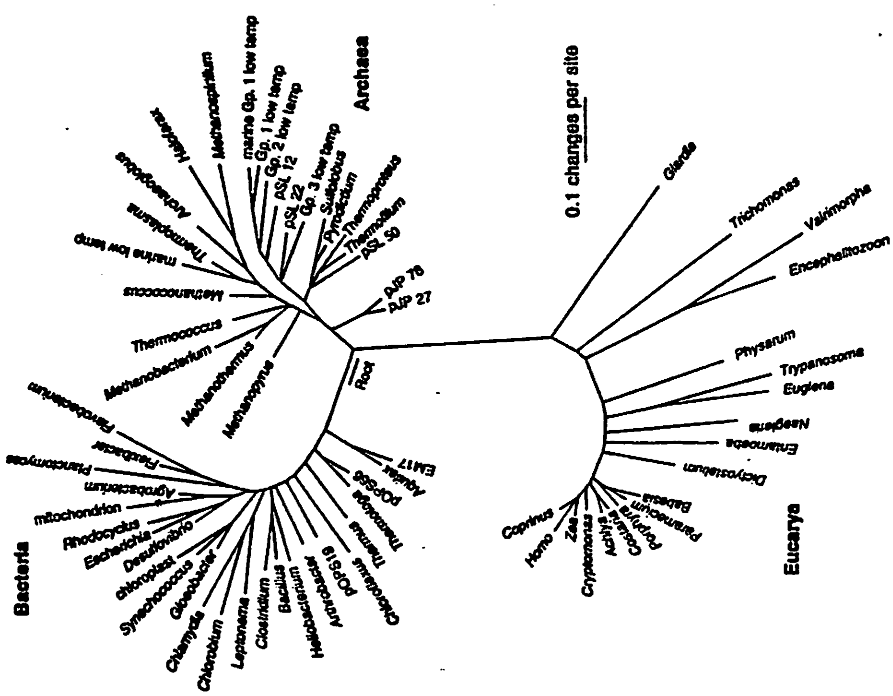


How do we classify life?

____



(Nealson, AREPS, 1997)



(Pace, *Science*, 276, 645, 1997)

What are some kinds of life in extreme environments?

Table 2 Metabolic types of prokaryotes

General type	Carbon source	Energy source	Electron donor	Electron acceptor
Heterotroph	Organic C	Organic C		
Aerobes			Organic C	O_2
Denitrifiers			Organic C	NO_3^-
Mn reducers			Organic C	Mn (IV)
Fe reducers			Organic C	Fe (III)
SRBs			Organic C	$SO_4^=$
Sulfur reducers			Organic C	S°
Methanogens			Organic C/H_2	CO_2
Syntrophs			Organic C	Organic C
Acetogens			Organic C/H_2	CO_2
Fermentors			Organic C	Organic C
Phototroph	CO_2	Light		
Cyanobacteria			H_2O	
Photosynthetic bacteria			S compounds, H_2, Organic C	
Lithotroph	CO_2/organic C	Inorganics		
H_2 oxidizers			H_2	O_2, NO_3^-, Mn (IV), Fe(III), $SO_4^=$, CO_2
Fe oxidizers			Fe (II)	O_2, NO_3^-
S oxidizers			H_2S, S°, $S_2O_3^=$	O_2, NO_3^-
N oxidizers			NH_3, NO_2^-	O_2
CH_4 oxidizers			CH_4	O_2

(Nealson, AREPS, 1997)

Lithoautotrophic Microbial Ecosystems in Deep Basalt Aquifers

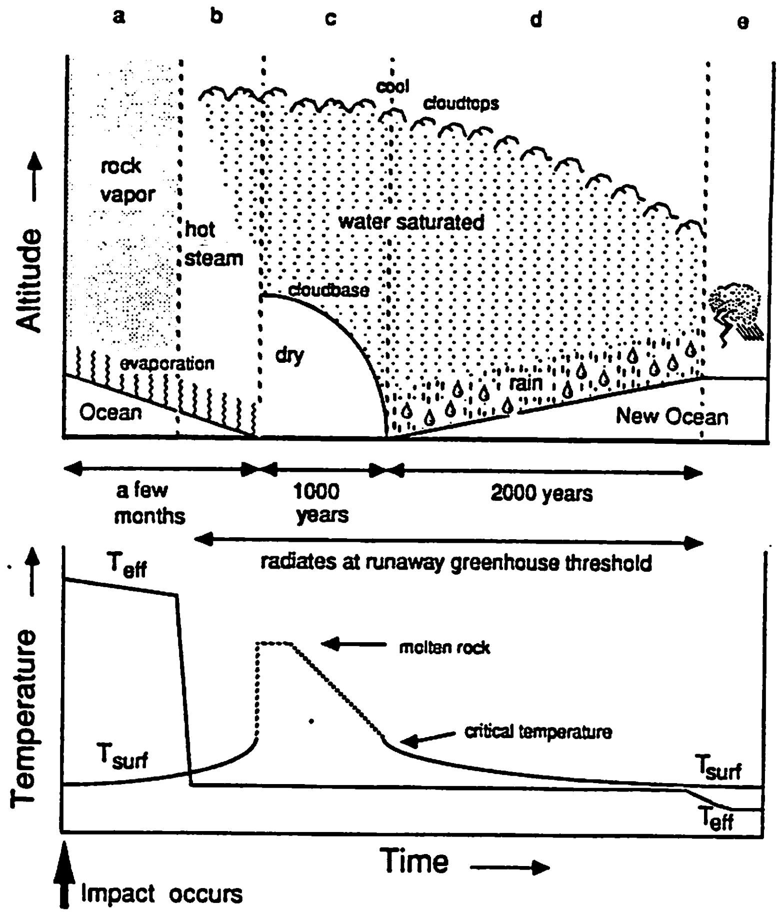
Todd O. Stevens* and James P. McKinley

Bacterial communities were detected in deep crystalline rock aquifers within the Columbia River Basalt Group (CRB). CRB ground waters contained up to 60 μM dissolved H_2 and autotrophic microorganisms outnumbered heterotrophs. Stable carbon isotope measurements implied that autotrophic methanogenesis dominated this ecosystem and was coupled to the depletion of dissolved inorganic carbon. In laboratory experiments, H_2, a potential energy source for bacteria, was produced by reactions between crushed basalt and anaerobic water. Microcosms containing only crushed basalt and ground water supported microbial growth. These results suggest that the CRB contains a lithoautotrophic microbial ecosystem that is independent of photosynthetic primary production.

(Stevens and McKinley, *Science*, 270, 450, 1995)

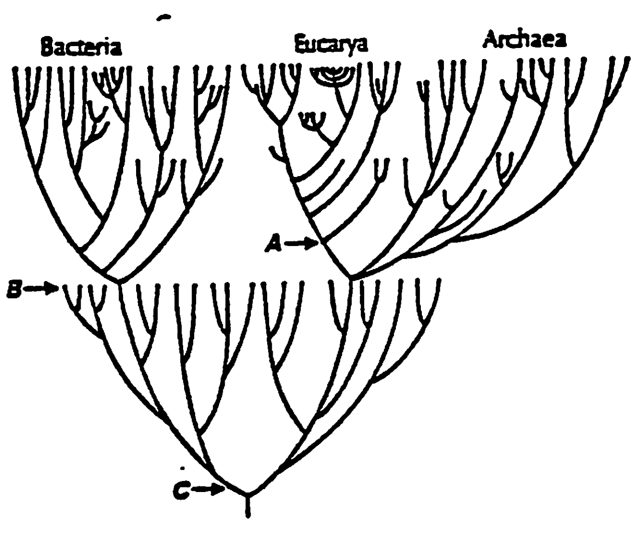
Why Yellowstone?

Thermophiles ...



(Zahnle and Sleep, in *Comets and the Origin and Evolution of Life*, Thomas et al. eds., 1997)

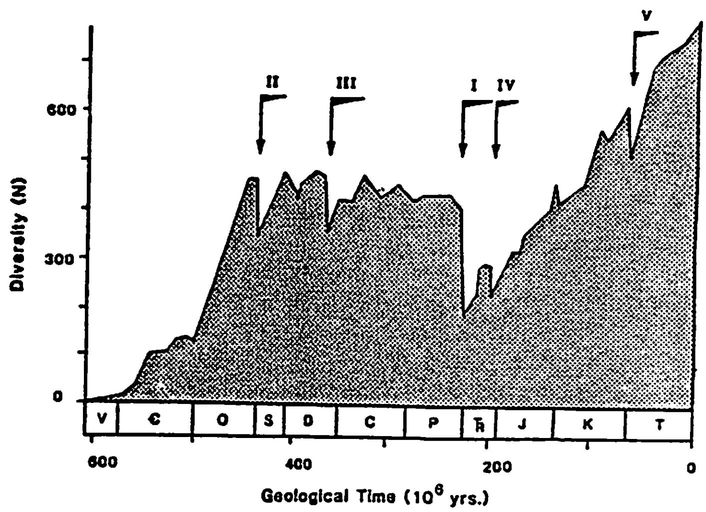
... impact frustration ...



(Gogarten-Boekels et al.,

Origins of life, **25**, 251, 1995)

... which leads to extinctions.



(McGhee, *The Late Devonian Mass Extinction*, 199

The planetary connection

The deep, hot biosphere

(geochemistry/planetology)

THOMAS GOLD

Cornell University, Ithaca, NY 14853

Contributed by Thomas Gold, March 13, 1992

ABSTRACT There are strong indications that microbial life is widespread at depth in the crust of the Earth, just as such life has been identified in numerous ocean vents. This life is not dependent on solar energy and photosynthesis for its primary energy supply, and it is essentially independent of the surface circumstances. Its energy supply comes from chemical sources, due to fluids that migrate upward from deeper levels in the Earth. In mass and volume it may be comparable with all surface life. Such microbial life may account for the presence of biological molecules in all carbonaceous materials in the outer crust, and the inference that these materials must have derived from biological deposits accumulated at the surface is therefore not necessarily valid. Subsurface life may be widespread among the planetary bodies of our solar system, since many of them have equally suitable conditions below, while having totally inhospitable surfaces. One may even speculate that such life may be widely disseminated in the universe, since planetary type bodies with similar subsurface conditions may be common as solitary objects in space, as well as in other solar-type systems.

(Gold, *Proc. Nat. Acad. Sci. USA*, **89**, 1992)

Why moose?

Yellowstone National Park - Glaciation Overview

K. Cyr

Chronology

3 million yrs ago - The start of the modern Ice Age, continuing through the present. Has had many intervals of glacial expansion separated by warmer interglacial intervals, including the one we're living in today. "No reason to believe that the ice age has ended." --Earth & Life Through Time, S. Stanley

1.7 my - Pleistocene Epoch begins. 14-18 minor glacial expansions during the Pleistocene, 1 every 10^5 yr or so with intensity of glaciation increasing over time. During glacial intervals, ice sheet development mostly in N. Hemisphere. 3 large glacial centers in North America, Greenland and Scandinavia.

150,000 yr and/or 100,000 yr - Bull Lake glaciation in Yellowstone Park. First of the 2 glaciations they know affected Yellowstone. Not much evidence for it remains so the dating is imprecise.

~45,000 yr to 15,000 yr - Pinedale (Wisconsin) glaciation in Yellowstone Park. Second and most recent glaciation that affected Yellowstone. There were several mini ice advances and retreats during this time.

14,000 yr - Ice has been retreating rapidly, and by now park lowlands are free of ice. The last glacial period is basically over.

10,000 yr to Recent - Holocene epoch.

Overview of Glaciation in the Park

Both the Bull Lake and Pinedale glaciations, the 2 major glacial events in the Park, started as Alpine or Mountain glaciations. Glaciers formed first in mountain tops, then as they grew they flowed down the valleys, joining other mountain glaciers, until they covered huge areas of land. Though there eventually was one huge ice sheet covering vast areas, the ice was fed by a bunch of different mountain glacier sources, so individual ice lobes within the ice sheet would advance and retreat on different timescales. This caused a lot of changes in flow direction of the ice, over time.

Past movements of glaciers are difficult to trace (especially if they change flow directions relatively often). Moraines, the piles of debris left behind by glaciers, are one of the main tracers used. However, later glaciations can easily wipe out earlier moraines, and this is the case in Yellowstone. There's only a little evidence of the Bull Lake glaciation left, but it indicates that the Bull Lake and Pinedale glaciations covered different areas. Bull Lake ice flowed to the West much farther than the Pinedale ice, but was totally obscured in the North by the extensive Pinedale flows. Pinedale ice covered huge areas of the park but didn't' really flow West, because large rhyolite lava flows occurred between the 2 glacial periods, blocking the westward movement of the Pinedale ice.

Pinedale ice flows (the most recent) in the Park consisted of a huge cover of ice over all but the SW edge of the park. The Yellowstone ice cap was centered N-S through Yellowstone Lake, and joined the various mountain glaciers from the North. The high country in the Park was completely overridden by the ice; the valleys and central plateau were under ~700 m of ice. One continuos glacial flow line was 146 km, "probably the longest glacier in the contiguous USA not originating from the Canadian icecaps".

Glaciation Effects on Yellowstone Park

Arretes, Horns - Glacial features caused by glaciers scraping along the sides (below the tops) of mountains. Because Yellowstone was completely covered by ice, these could not form in the Park itself, but examples can be seen outside the Park e.g. to the NE outside of Cooke City.

Obsidian Cliffs - The Obsidian Cliffs are thought to have formed when the Bull Lake ice met the recently extruded lava, cooling it extremely quickly.

Grand Canyon - The glaciers did not scrape out the canyon. Glaciation before Pinedale filled the canyon with ice and protected the walls from glacial scouring, as a regional glacier flowed across the canyon and not down it. Large glacial erratics were left on the rim near Artist's Peak; the erratics came from the Beartooth Mountains in the NE.

Hayden Valley - Ice dammed the Yellowstone River near Canyon Village, forming "Hayden Lake" in what is the Hayden Valley (no lake) area today, located NW of Yellowstone Lake.

"Retreat Lake" - At the end of the Pinedale glaciation a lake formed filling the Grand Canyon. Ice receded so there was none in the Canyon, but the lower end of the Canyon was blocked by the SW margin of a lobe of ice damming the river and forming a huge lake of meltwater . The lake filled the Canyon to a depth of 180m (590 ft).

Catastrophic Flooding - Lakes often form at the end of glaciers: a river gets dammed by an ice lobe, melt water backs up forming a huge lake. Eventually the lake is huge enough that the ice dam floats in it and water bursts out beneath the ice dam, flooding nearby areas.

At least 2 large floods occurred, down the Lamar and Yellowstone rivers as the Pinedale Ice retreated. Water was 45-60m (150-200ft) deep. Evidence includes ripped up alluvial fan deposits and channel bars. E.g. NW of Gardiner, MN flood deposits between the road and river form a river channel bar 20m high by 450 m wide which is covered with giant ripple marks.

Effect of Geothermal Activity on Ice - Near Mammoth Hot Springs, late Pinedale ice melted erratically (due to the heat sources), leaving large isolated blocks of ice surrounded by sediment left by receding ice. When the ice blocks melted they formed a series of alternating lakes and small hills called kettles and kames. Other various mounds of debris were melted out by the hot springs, and dot the landscape.

Yellowstone hot springs and geysers (currently) produce enough heat annually to melt ice 5 m thick over the entire area of the geyser basins. Since the entire area was covered by ice during the glacial periods, ice was being supplied fast enough to make up for the melt.

Glossary of Glacial Features

Arrete - A steep sided mountain ridge formed when glaciers scraped along 2 sides of a mountain or when several cirques form along 2 sides of a mountain ridge.

Bergschrund - Boundary between flowing glacial ice and a snowfield at the glacial edge.

Cirque - a steep-walled, half-bowl shaped hollow (tilted bowl) situated high on the side of a mountain, produced by the erosion from a mountain glacier which formed in and flowed out of it, plucking away the bedrock.

Drumlin - A streamlined hill of glacial till deposited and shaped by moving glacial ice. Usually teardrop shaped with the blunt end facing 'upstream'.

Erratic - A boulder gouged out of bedrock by glacial ice, carried along by the ice and eventually dropped when the ice recedes. Often of quite different composition than the surrounding rock, indicating they were moved long distances.

Hanging Valley - A glacial valley whose mouth is at a relatively high level on the steep side of a larger glacial valley. The larger valley was scoured out by the main body of a glacier; the hanging valley above it was scoured out by a smaller, tributary glacier. The main glacier was bigger and thus eroded the main valley more deeply.

Horn - Pyramid shaped peaks formed by glaciers eroding cirques on 3 or more sides of a mountain. Examples: the Matterhorn in Switzerland, Pilot and Index Peaks NE of Yellowstone Park.

Interglacial - A warm period between glaciations in which the climate warms to at least the present level.

Interstadial - A relatively warm climatic episode during a glaciation, marked by temporary retreat of ice. Not as warm as an interglacial interval.

Kettles and Kames - Blocks of ice are left behind as glaciers retreat. The blocks become buried by glacial outwash sediment, eventually melt forming lakes (Kettles) alernating with small hills of debris--the remainder of the outwash sediment (Kames).

Moraine - A mound or ridge of unsorted glacial debris (sand, silt, pebbles, cobbles, boulders), deposited by glacial ice. Terminal moraine - the end moraine marking the furthest advance of a glacier or ice sheet. Lateral moraine - the moraine deposited at or near the side margin of a mountain glacier.

Outwash - Sediments deposited by streams flowing from the fronts of glaciers.

Tarn - A lake that forms in a cirque.

Till - Unsorted glacial debris (from clay to boulders) laid down directly by glacial ice. It is the material that makes up moraines.

U Shaped Valley - A valley carved out by a glacier has a characteristic U shape (broader bottom, gentler sloping) as opposed to the V shaped valleys formed by stream erosion.

Figures:

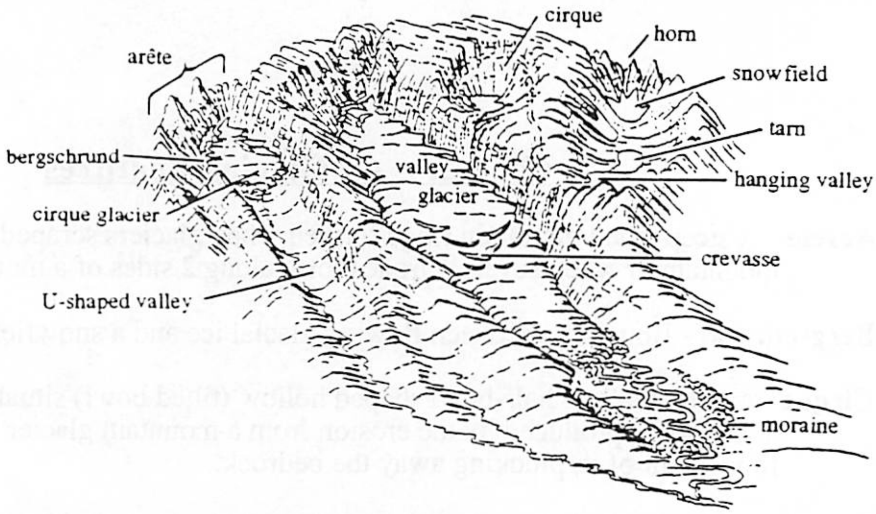


Figure 5.18. Mountain glacial features prominent in Glacier National Park. (From Carrara, 1993; sketch by T. R. Alpha, 1991.) Ice Age History of Ntl Parks

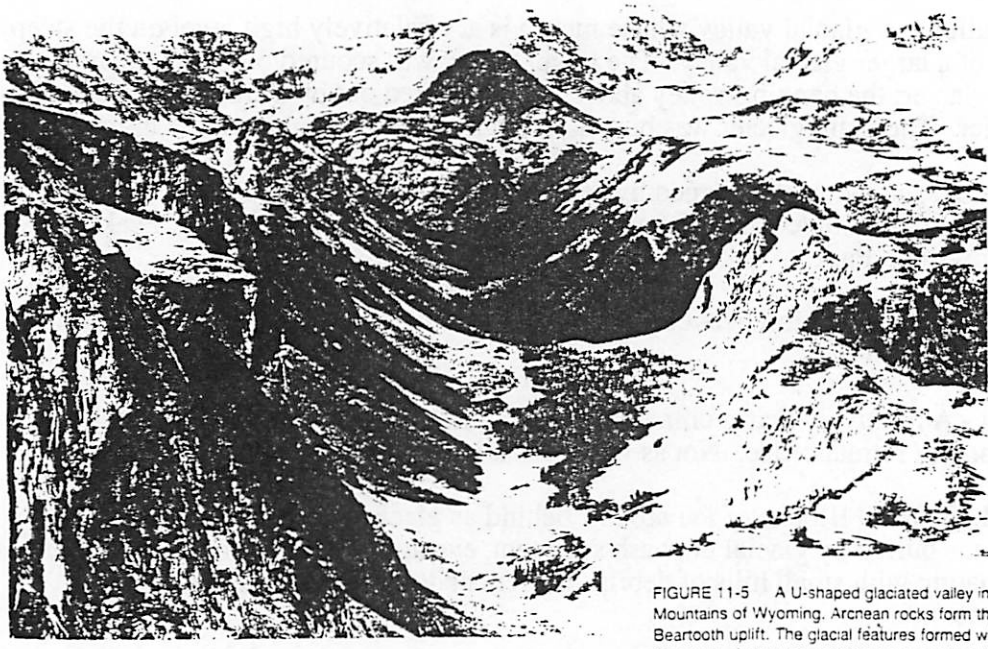


FIGURE 11-5 A U-shaped glaciated valley in the Beartooth Mountains of Wyoming. Archean rocks form the core of the Beartooth uplift. The glacial features formed within the last 2 million years, during the earth's most recent Ice Age. *(National Park Service.)* Earth Life Thru Time

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Pierce, Kenneth L. (1979) History and dynamics of glaciation in the northern Yellowstone National Park area. Geological Survey Professional Paper 729-F (Washington: US Gov Printing Office).

Stanley, Steven M. Earth and Life Through Time. 1989. (New York: WH Freeman and Co.).

AERIAL GEOLOGY

(trilling!)

What We Will See (see included maps)

Tucson -- Salt Lake City

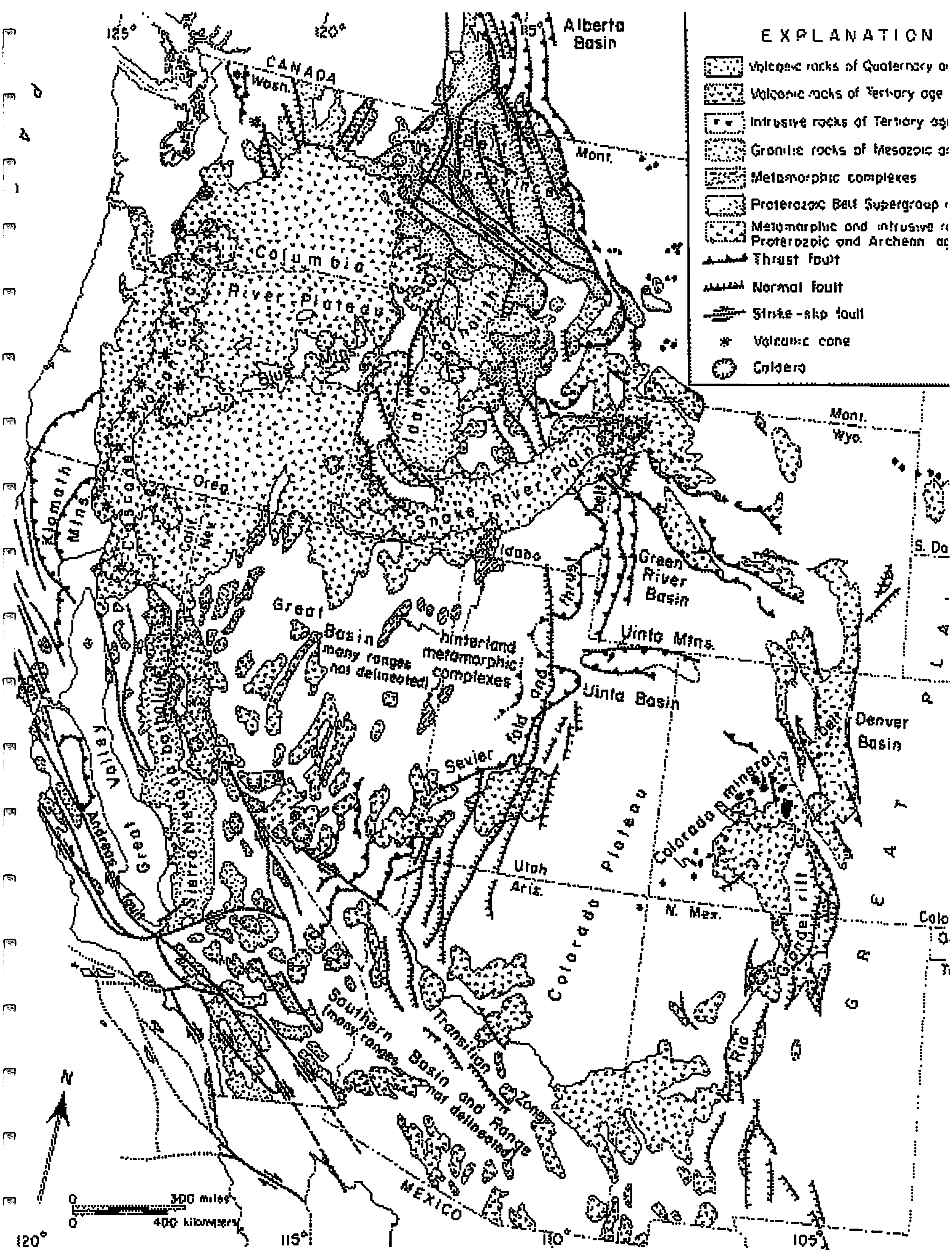
1 Basin and Range
2 Transition Zone/Mogollon Rim
3 Colorado Plateau
4 Meteor Crater
5 Grand Canyon (Really cool from the air!)
6 Utah National Parks (Zion NP, etc.)
7 Great Salt Lake ("This is the place")
8 Bonneville Salt Flats (formerly Lake Bonneville)
9 Uinta mountains (the only major E-W mountain chain in the West)
10 Wasatch mountains and Wasatch Front

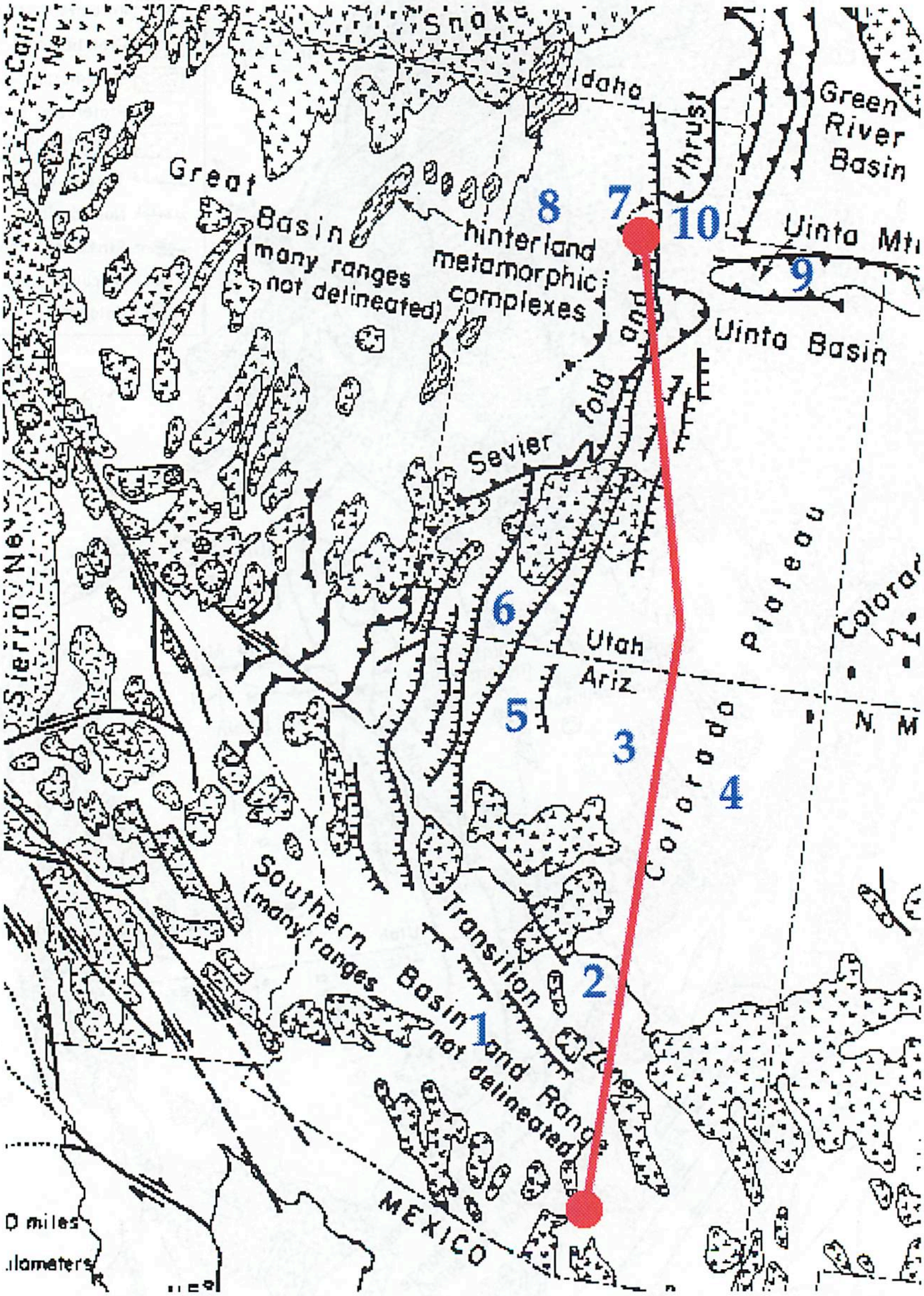
Salt Lake City -- Bozeman

10 Wasatch Mountains and Wasatch Front
11 More Basin and Range
12 Snake River Plain and Basalts
13 Yellowstone NP, Yellowstone Lake
14 Grand Tetons (NP)
15 Teton Fault
16 Rocky Mountain Fold Thrust Belt (a real whopper!)
17 Great Plains Province

Other Kinds of Things to Look For

Erosion Landforms (for instance, at Zion NP)
Meanders (Colorado River but also all smaller streams)
Canyons (comparison, e.g. to flow and flood marks seen on Mars)
Lots of different kinds of clouds
Atmospheric phenomena -- boundary layer, etc.
Glacial Features? look for kettles, drums, eskers, etc.
Mines (strip mines)
Sedimentary Layers (e.g. at the Canyon)
Optical phenomena, such as glories (rainbows around shadows of airplanes)
Landslides?
Dendrite-type canyons and erosion (comparison to Mars)
Moose


EXPLANATION
Volcanic rocks of Tertiary age
Metamorphic complexes
Metamorphic and intrusive
Proterozoic and Archean
Thrust fault
Normal fault
Strike-slip fault
Volcanic cone
Caldera
125°
120°
115°
110°
105°
Alberta Basin
CANADA
Wash.
Mont.
Columbia River Plateau
Idaho batholith
Snake River Plain
Oreg.
Klamath Mtns.
Calif.
Nev.
Idaho
Green River Basin
Great Basin
many ranges not delineated)
hinterland metamorphic complexes
Uinta Mtns.
Uinta Basin
Mont.
Wyo.
Denver Basin
Sevier fold and thrust belt
Great Valley
Sierra Nevada batholith
San Andreas fault
Colorado Plateau
Colorado mineral belt
Utah
Ariz.
N. Mex.
Colo.
Rio Grande rift
Transition Zone
Southern Basin and Range
(many ranges not delineated)
MEXICO
N
0
300 miles
400 kilometers
S. Dak.


Snake
Idaho
Calif
Nev
Great
Basin
(many ranges
not delineated)
hinterland
metamorphic
complexes
thrust
Green
River
Basin
Uinta Mt
Uinta Basin
Sevier
fold and
Sierra Nev
Utah
Ariz.
Colorado
Plateau
N. M
Southern Basin and Range
(many ranges not delineated)
Transition Zone
MEXICO
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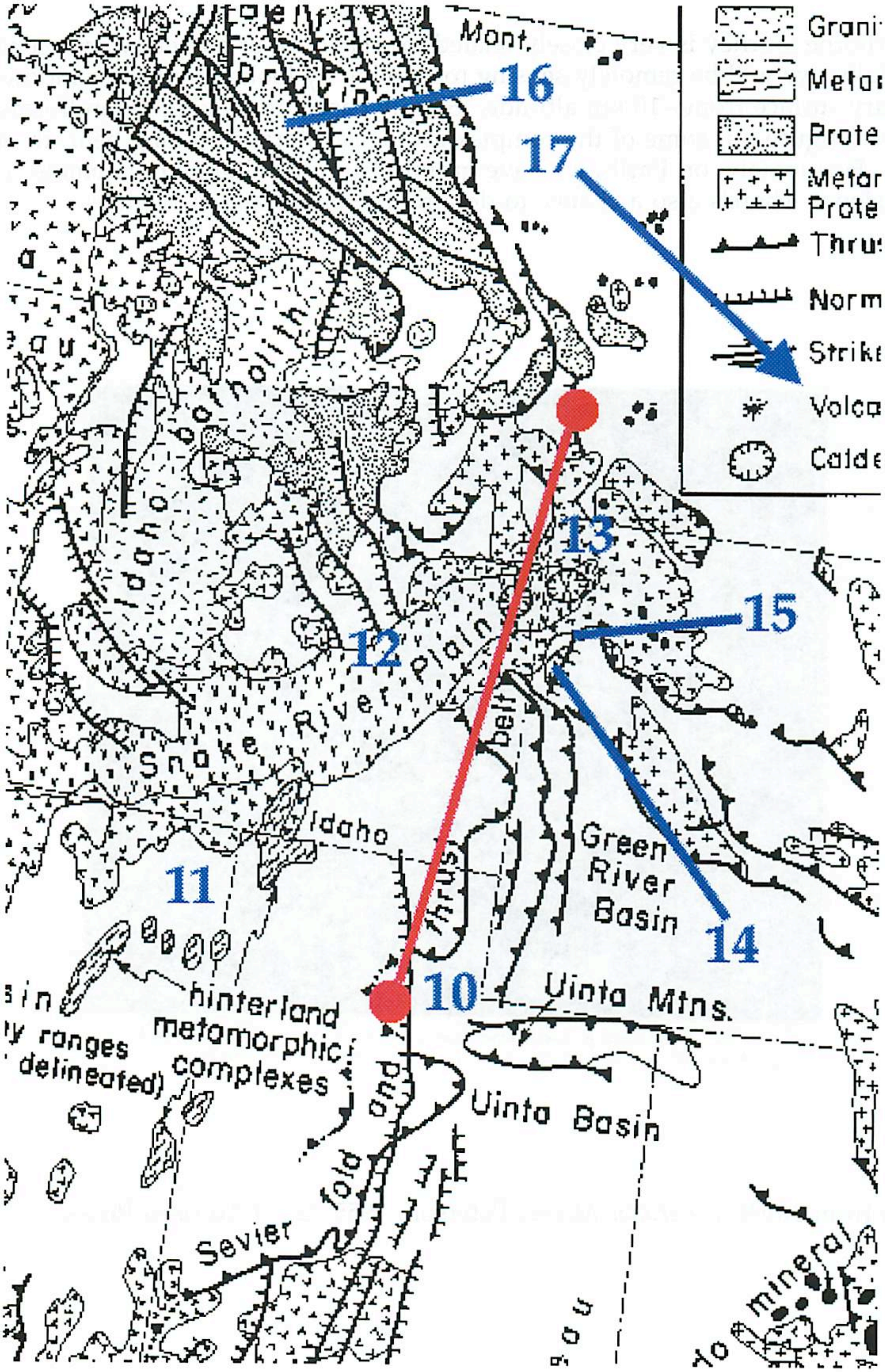
Grani
Metar
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Metar
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Thrus
Norm
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Volca
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16
17
Idaho batholith
13
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12
Snake River Plain
belt
Idaho
Thrus
Green
River
Basin
14
11
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Uinta Mtns.
hinterland
metamorphic
complexes
ranges
delineated)
Uinta Basin
Sevier fold and
mineral

Aerial Geology: The Planetary Connection

Our airborne journey is very closely related to what a lot of planetary science is. Essentially, we will be remotely sensing (observing by looking out the windows) a planetary surface from ~10 km altitude. Simply based on looking at landforms, we can try to figure out some of the complex geological story unfolding beneath our wings. Fortunately, on Earth, we have ground truth to calibrate our remote sensing conclusions. There's also a chance to do airborne observations of moose.

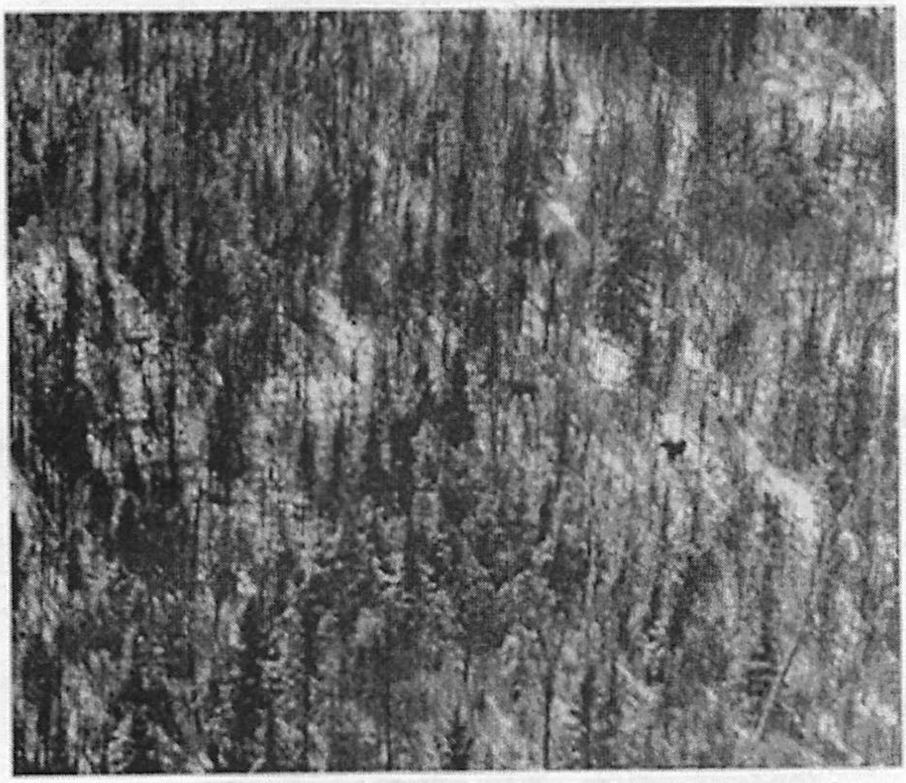


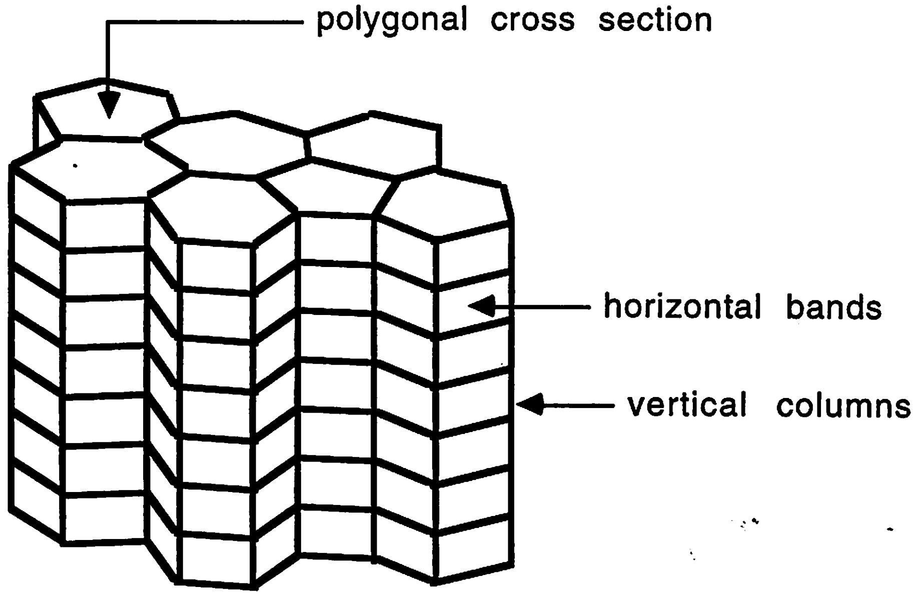
FIGURE 59. Two moose in mixed hardwood and conifer forest as they appear from an aircraft. North of Wanapitei Lake, Sudbury District. February 5, 1947

(Photo from *North American Moose*, Peterson, 1955, U. of Toronto Press)

Columnar Jointing in Yellowstone National Park

Joe Spitale

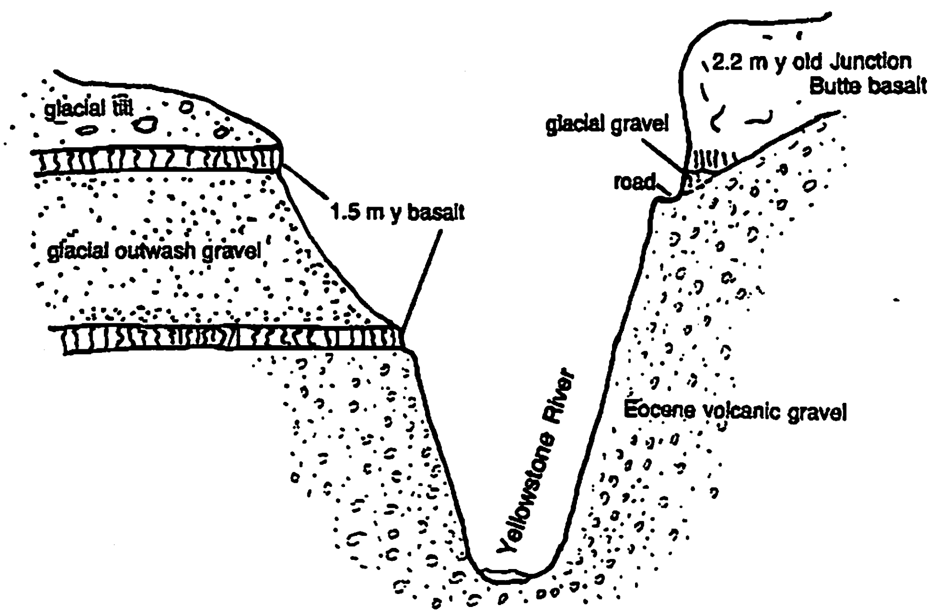
Columnar jointing is characterized by long, usually vertical, columns of rock with polygonal cross-sections. It can be found in lava flows, shallow intrusions and welded tuffs[2]. The jointing is a result of tensile stress generated during contraction of a cooling lava. As the surface of the magma cools below the point where tensile stress cannot be relieved through plastic deformation, cracks form and propagate across the surface. As cooling proceeds inward, existing joints propagate into the magma forming long columns. Column faces generally display a transverse banding suggesting that the inward propagation occurs in a series of discrete events, each producing a single band[2].



Theoretically, the release of tension is most efficient when the cracks are arranged such that each fracture forms an angle of 120 degrees with every adjoining crack. The only such arrangement is hexagonal[1]. In addition, joints may intersect at right angles. This happens when a new joint propagates toward an existing joint. The existing joint is a free surface, so the principle stresses must be parallel and perpendicular to the surface, resulting in an intersection which is perpendicular[2].

Since cooling proceeds inward from every surface, discontinuities occur in the columnar structure at the places where joints propagating from different surfaces meet. In tabular lava flows, this results in two "colonnades" - one formed by columns propagating downward from the top, the other formed by columns propagating upward from the bottom.

The exact configuration of the columns depends on the properties of the lava from which they form[4], so observations of columnar joints can give information about the cooling process. In the simple case of a tabular lava, columns are oriented perpendicular to the isothermal surfaces, although in more complicated bodies like lava tubes, this is not necessarily the case[2]. The spacing of the columns may be a reflection the thermal gradient during cooling. The relative heights of the colonnades in a tabular lava are an indication of the relative rates of cooling through the upper surface and lower contact of the body. Inhomogeneities in the lava will cause imperfections on the hexagonal structure. The joint faces record details of the fracture propagation[2].



from [3]

Overlooking the Yellowstone river near Tower Falls are two basalt flows exhibiting columnar jointing, which were extruded onto the Yellowstone

Plateau about 1.5 million years ago[3] along with the more common rhyolite flows[5]. Unfortunately, the tops of the columns are covered by glacial till, so the polygonal jointing pattern cannot be seen clearly, although it should be evident in the shapes of the columns.

[1] C.N.Beard; *Quantitative Study of Columnar Jointing* Bulletin of the Geological Society of America v70, p379; 1959

[2] J.Suppe; *Principles of Structural Geology* Prentice Hall; 1985

[3] W.J.Fritz; *Roadside Geology of the Yellowstone Country* Mountain Press; 1985

[4] A.V.G.James; *Factors Producing Columnar Structure in Lavas and Its Occurrence Near Melbourne, Australia* Journal of Geology, v28, p458; 1920

[5] W.R.Keefer; *The Geologic Story of Yellowstone National Park* Geological Survey Bulletin 1347, United States Government printing office 1972

Supposed Glacial Features on Mars

Background

The question of the presence of water on Mars has been prominent for as long as Mars has been the subject of scientific inquiry, dating back to the canals of Lowell and a number of reports of spectroscopic identification of water vapor in Mars' atmosphere. Modern observations, particularly by the Mariner and Viking probes, showed that water was certainly not plentiful on the surface or in the atmosphere, but simultaneously revealed many landforms suggestive of the influence of water.

Leaving aside for the moment the question of liquid water on the surface and the climactic difficulties it poses, apparent glacial and periglacial features were identified in the years following the Viking missions. The first features identified as such were very low-key and unimpressive: evidence was found of slow downhill creep of surface material consistent with freeze-thaw induced creep.

The first suggested evidence of actual glacial activity was by Lucchitta, who pointed out that a number of features in the Martian outflow channels strongly resembled ice-carved features on the Earth. While there is strong evidence that the channels were carved by catastrophic floods, Lucchitta proposed that Alpine-style glaciers could have formed and moved down the pre)carved channels, adding their own distinctive touches to the local morphology. In Lucchitta's model, these glaciers were localized and transient phenomena, resulting from scattered springs and minor floods.

The next major work was by Baker et al, in their "ancient oceans" model. They proposed a massive ancient hydrologic cycle, which included extensive glaciers. Identifying a great number of possible glacial features, each of which was perhaps questionable on its own, they noted that their relative positioning made sense as part of a grand assemblage caused by glaciation. Much of the recent work on glacial landforms has been sparked by this work.

Particular Features

1. Alpine Glaciation In The Outflow Channels?

Most of the evidence for glacial activity in the outflow channels involves reinterpreting features which had been previously attributed to catastrophic flooding. Lucchitta notes that most of the morphologic qualities are consistent with glacial valleys: specifically that they both widen and constrict along their length; that they are deeply incised; that they anastomose around islands; and that at constriction points, the channels become U-shaped.

This last point is worth a bit more consideration. U-shaped valleys are a characteristic feature of glacial valleys on Earth, but if the channels are glacial in origin, why are only the constriction points U-shaped? A proposed solution is that the channels are the result of flooding with significant surface ice; at the constriction points, the ice accumulates, producing localized glaciers.

Other cited features include: long, even terraces along the sides of the channels, resembling similar, glacially scoured terraces on the Earth; long, regular ridges and grooves which are similar to features in the Scablands but also to flutes carved by glaciers; thin ridges at the mouth of Ares channel resembling end moraines and kame complexes; and hanging valleys.

The ridges and grooves mentioned above are a perfect match for neither the Scablands features nor for glacial flutes. Grooves carved by the Scablands flood are much smaller, implying that Martian floods would have had to have been much larger. Glacial flutes, on the other hand, tend to be much shallower, implying that Martian glaciers would probably have to have been repeated many times.

Hanging valleys are particularly intriguing. While not exclusively caused by Alpine glaciation, they are usually considered a diagnostic indicator of its presence.

2. Continental Glaciation?

Following the publication of their 'ancient oceans' model in 1991, the group of workers including V.R. Baker, R.G. Strom, and J.S. Kargel identified a number of features as being possibly glaciogenic. While suggesting various terrestrial analogs for these features, they placed more emphasis on the sequences of features and the whole assemblage of features.

In particular, the area around Hellas Basin was analyzed. An area dominated by ridge-and-trough structure was analogized to glaciated lineated terrains in Canada. An area of streamlined ridges and equant hills was interpreted as drumlinoid terrain. Long sinuous ridges were considered likely candidates for eskers. Cuspate ridges were identified as terminal and recessional moraines. Figures 1 and 2 (from Kargel et al.) show the assemblage of features and the derived ice flow patterns.

Switching to the northern hemisphere, this group focussed on the so-called "thumbprint terrain." The curvilinear patterns that give the terrain its name were ascribed to a variety of moraines, while apparent eskers and kame complexes were identified as well. The occurrence of a large patch of thumbprint terrain near the equator is a particularly interesting fact in this context. Figure 3 (from Lockwood and Kargel) shows a patch of thumbprint terrain along with their assignments of origin.

Of all the features given glacial origins by this group, the identification of eskers has attracted the most attention. Heinz states that the orientation of the features is in the wrong direction for eskers and proposes massive ancient mud floods. Metzger notes significant differences between the Martian 'eskers' and those in New York state.

3. Volcano/Ice Interaction?

While not one of the 'classic' glacial features, some workers have identified some features as being consistent with volcanoes forming in a glacial environment. Chapman identifies the basal scarp of Elysium Mons as possibly resulting from ice confining lava flows. Lescinsky and Fink note a variety of typical features with an eye towards future missions being able to resolve them.

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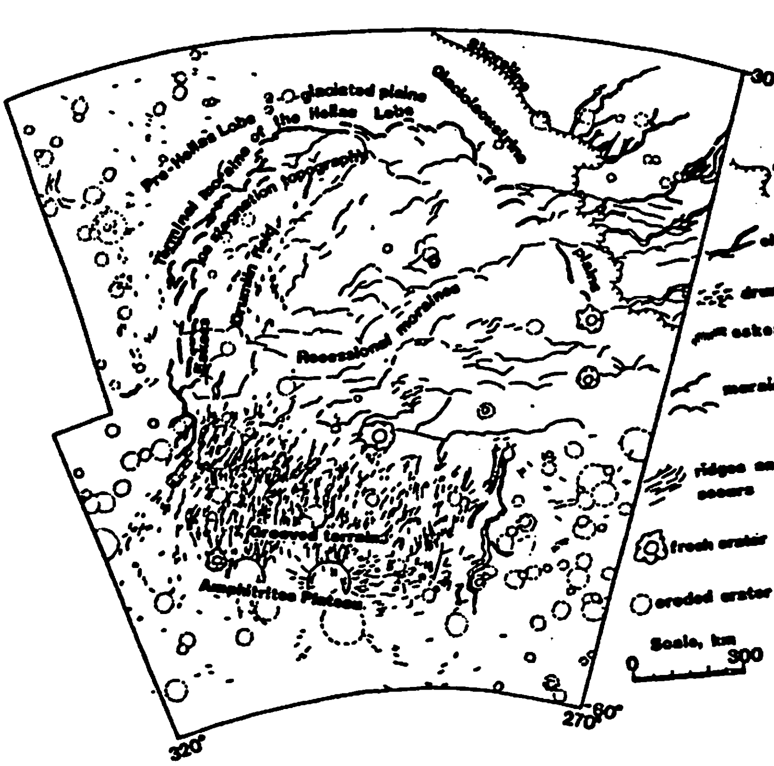


Figure 1. Distribution of selected glacial features in Hellas.

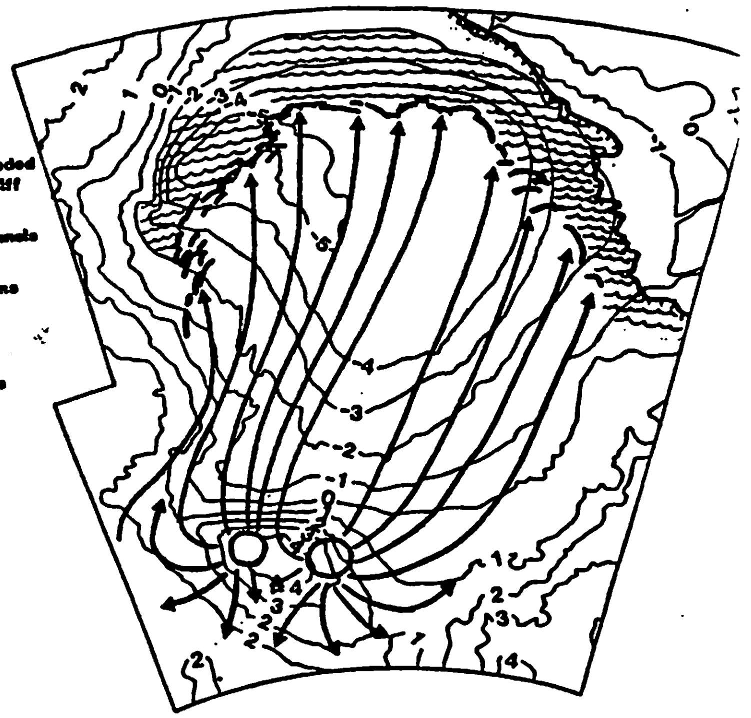


Figure 2. Schematic ice flow lines and former distribution of glacial ice and a proglacial lake in Hellas.

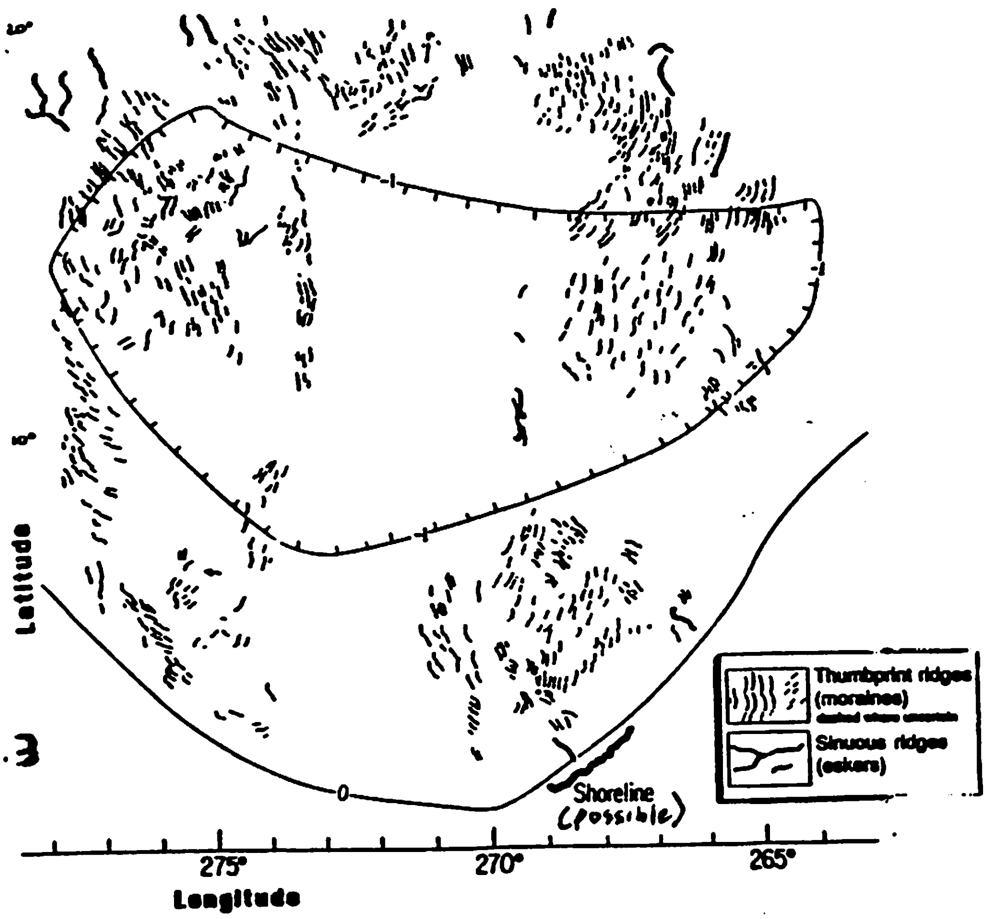


Fig.3

A Tale of Two Magmas: Bimodal Magmatism

Peter Lanagan

Bimodal Magmatism in Yellowstone

A quick look at a geologic map of the Yellowstone area will show that rhyolitic materials dominate the surface. One will also note pockets of basaltic volcanism. However, there are few materials of intermediate composition. What gives?

Look at the diagram (purloined from Leeman, 1989) on the next page.

A. *Introduction of hot spot basaltic magmas.* (Presently NE of Yellowstone) Basaltic magma from the hot spot plume is injected into the crust. The magma rises until it is neutrally buoyant with respect to its surroundings where it then expands laterally. Some of the surrounding crustal rocks may melt to form somewhat more silicic magmas. These less dense, relatively more silicic magmas rise.

B. *Plumbing system.* More basaltic magma rises into the crust from the hot spot. Melting of silicic materials continue. The silicic magmas rise and form more shallow crustal reservoirs. The composition of these magmas is uncertain; however, they are inferred to be the parent magmas of the Yellowstone rhyolites. It is thought that the silicic magmas rise slowly enough through shallow zones that they have time to have their volatile contents equilibrate to the lower pressures, so rhyolitic volcanism is infrequent in this stage. As the shallow magma chamber grow, the crust thermally expands and regional uplift may occur. Also, the rising magmas may give rise to fracture systems.

C. *Rhyolitic volcanism.* (Yellowstone in violence) There is little basaltic volcanism at this stage. Any basalt that does manage to rise to shallow depths is quenched by the cooler silicic magmas. As a result, the basalt may pool beneath the silicic magma chambers. Heat conducted from the basaltic magmas may prolong the cooling of silicic magmas. This is important, for higher viscosity rhyolitic magmas may freeze in place before extruding, despite their lower melting points. As the silicic magma chamber grows, the magma is differentiated as more buoyant rhyolitic magmas rise to the top of the magma chamber. Fractures created in the previous stage may allow groundwater to seep into the silicic magma chamber. Incorporation of a large quantities of this volatile material into the rhyolitic magmas have explosive results.

D. *Basaltic Volcanism.* (Present Snake River Plain) Material in silicic magma chambers eventually cool and solidify. This is due to the (violent) removal of the most volatile components of the silicic magma chamber. Because basaltic magmas cannot rise through the less dense rhyolitic plutons, the subsequent period of basaltic volcanism starts around the edges of the rhyolitic source area. However, fractures through the old rhyolitic magma chambers (perhaps caused by chamber collapse) eventually allow basaltic magmas to rise through what was once the center of rhyolitic volcanism.

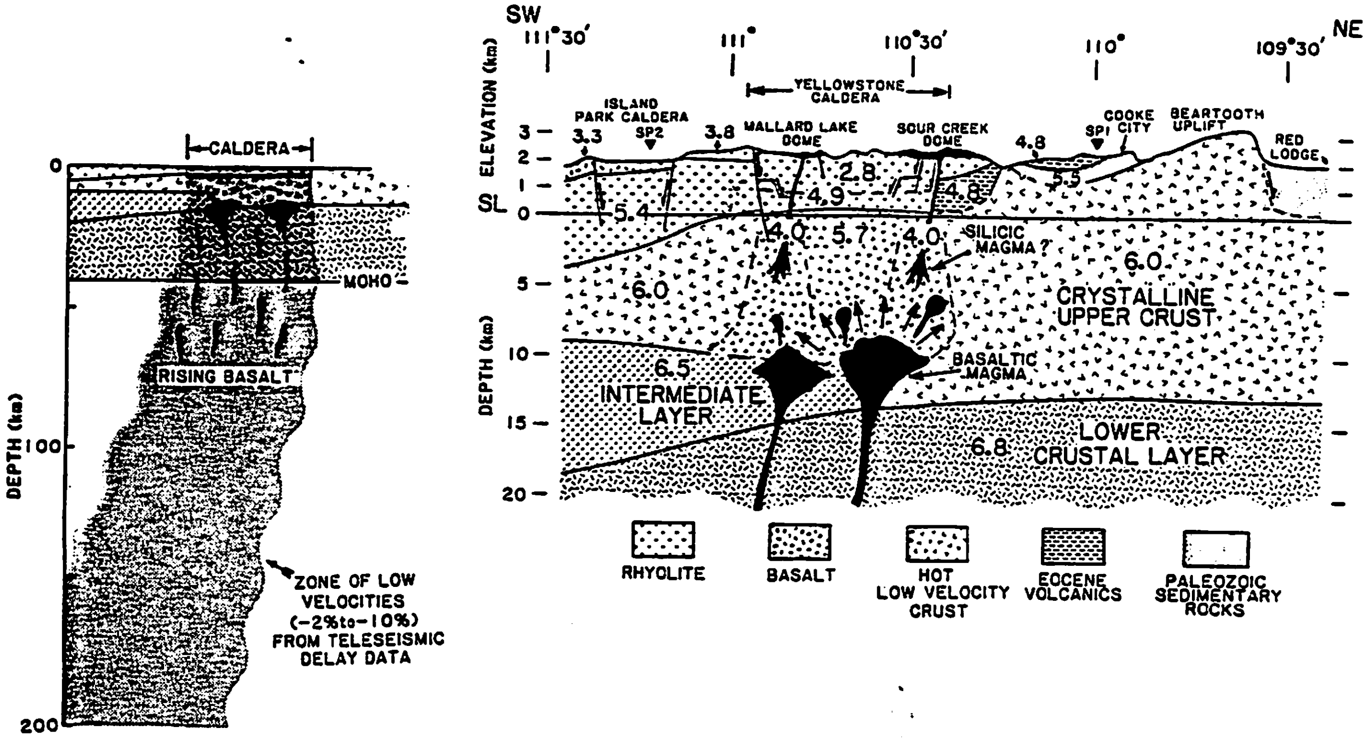
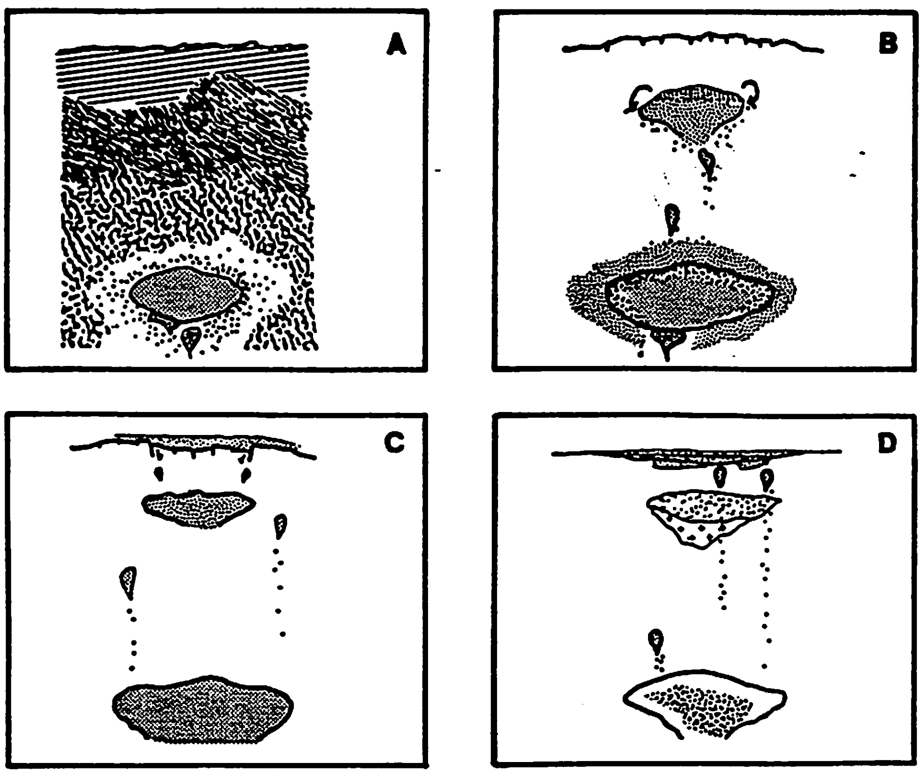


FIGURE 7.9 Idealized NE-SW geologic-seismic velocity model for the crustal structure of the Yellowstone-Island Park-Snake River Plain region. *P*-wave velocities are in kilometers/second (from Braile *et al.*, 1982; Smith *et al.*, 1982). Geologic interpretations are based on constraints of the Quaternary history and the petrologic models of Christiansen (U.S. Geological Survey, personal communication, 1978, and in press) and Leeman (in press). Low velocities in lower crust and upper mantle inferred from teleseismic delay studies (Iyer *et al.*, 1981). Model for basaltic melt rising from the upper mantle into the crust is from Hildreth (1981).

Smith + Braile (1984)

Leeman (1989)



Other Terrestrial Places of Interest

- **Grandfather Mountain Window** (NW North Carolina)
- **Cadillac Mountain Complex** (Maine)
- **Iceland**

The Planetary Connection

If a molten material is emplaced under another material with a lower melting point, then one may see some bimodal character in the resulting magma system..

- **Mars:** Terrain around Alpollinaris Patera have been interpreted to consist of pyroclastic materials overlain by basalts. The two different eruptive styles could be due to compositional differences between the magmas in question. However, the different eruptive styles may have more to do with the consumption of volatile materials over time in the subsurface.

- **Anyone for nonsilicic bimodal magmatism?:** How about cryo-bimodal magmatism? This could involve a similar process involving two nonmixing eutectic mixtures of different compositions with different solidus temperatures. There wouldn't be much heat to conduct, but it has been noted that a little heat on a sufficiently cold body can result in effusive activity. (i.e. geysers on Triton)

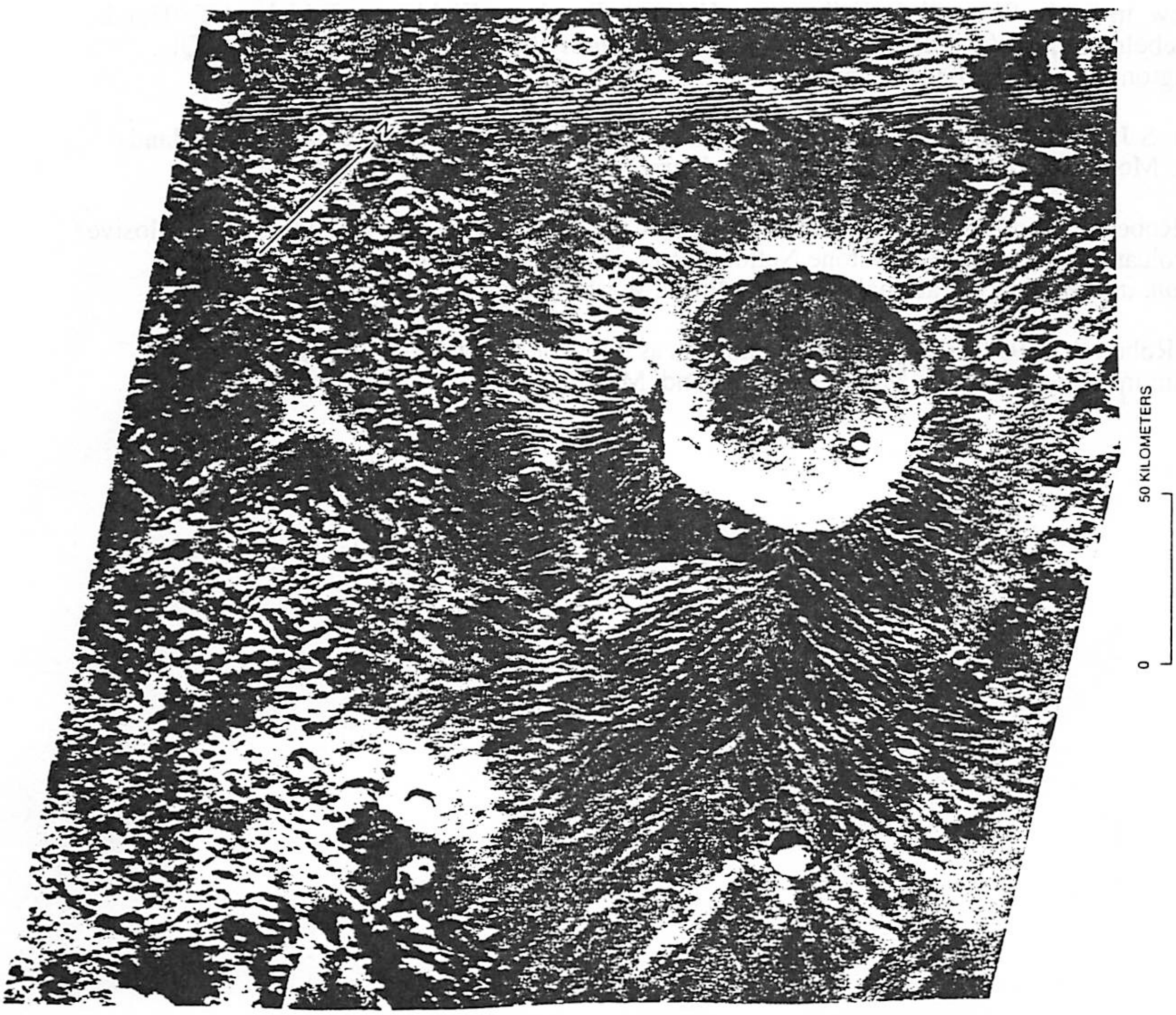


Figure 23. Apollinaris Patera. A, Apollinaris Patera and shield, relatively isolated at northern margin of old cratered highlands. Caldera apparently overflowed extensively on southeast side, forming broad fan of ash or lava that obscured basal escarpment surrounding volcano; fan displays dendritic network of distributary channels. Flanks of shield are highly dissected. Sun illumination from top. Viking Orbiter frame 372S56.

Hodges and Moore (1994)

Bimodal Magmatism

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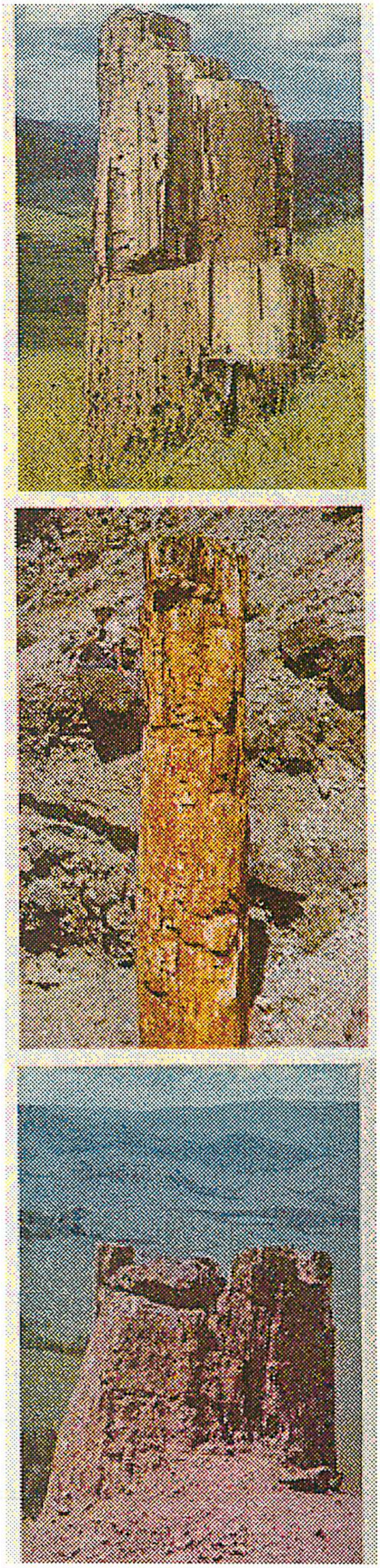
The Fossil Forests of Yellowstone

Nancy Chabot

About 50 million years ago (Eocene time), there were volcanic eruptions in Yellowstone. The nearby forests were buried by ash, mud flows, and stream deposits, and silica-rich water filled the cavities in the wood, petrifying them. Leaves, needles, cones, and pollen grains were also preserved. Altogether, almost 200 different types of planets are represented in the fossil forests of Yellowstone.



PETRIFIED TREE TRUNKS: All 3 of these trunks were photographed near Specimen Ridge (see map on following page for location). The trees shown are pine (top), sycamore (middle), and redwood (bottom). Photos from Dorf, 1964.

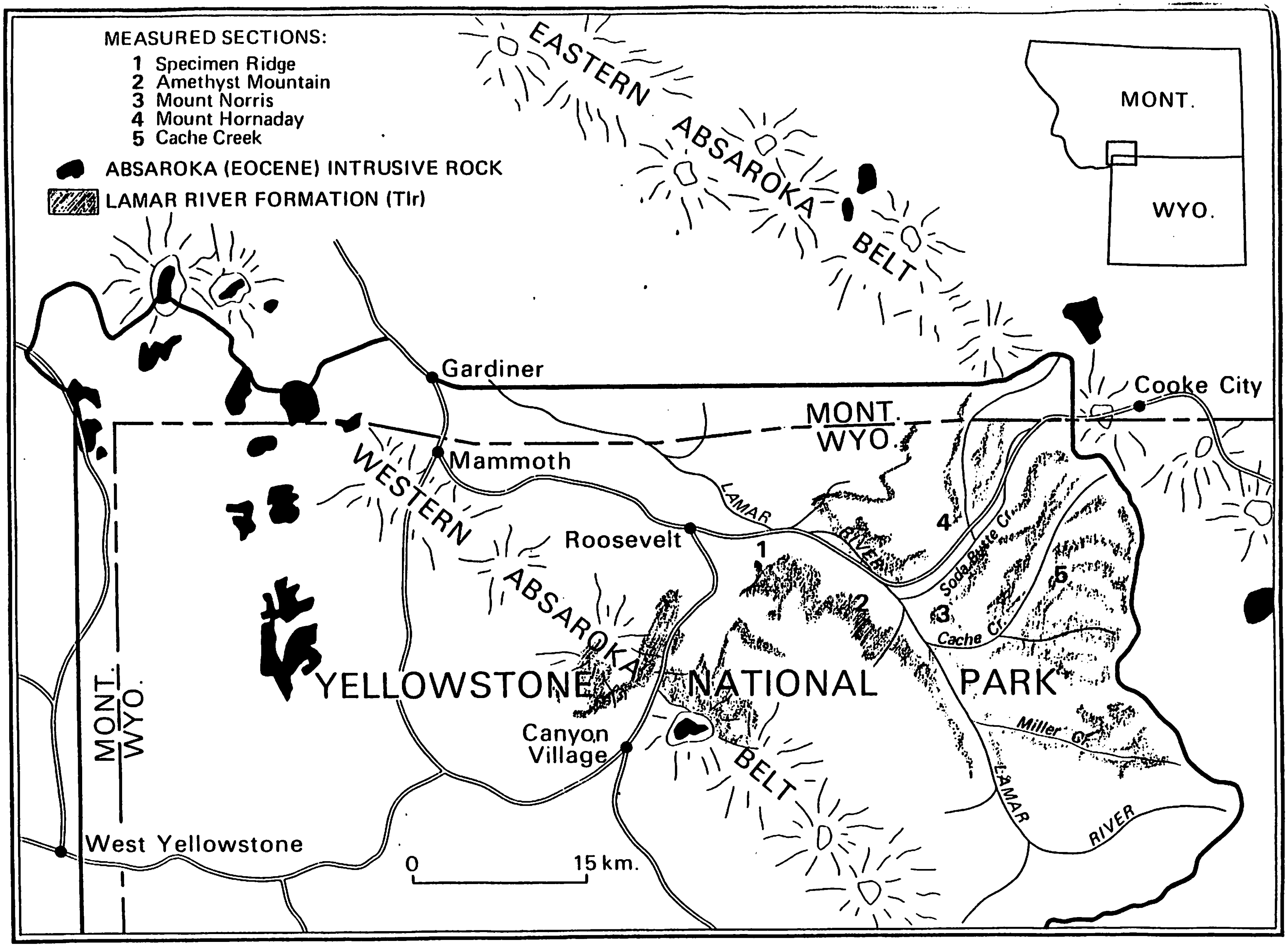
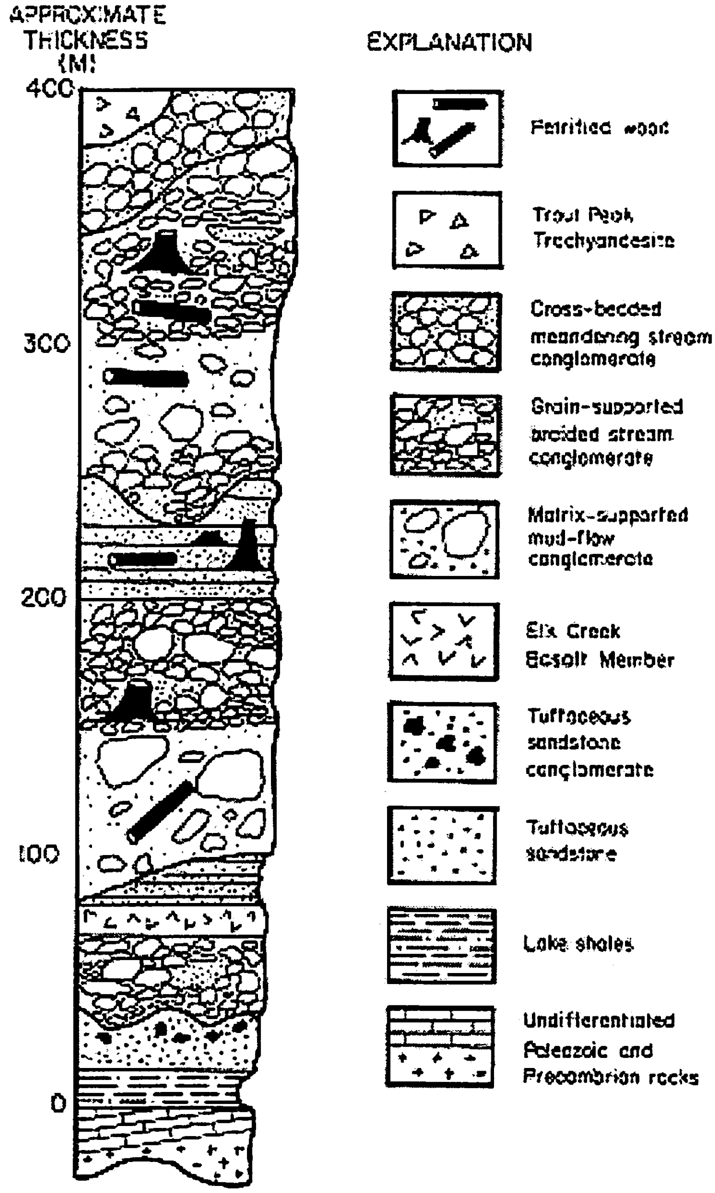
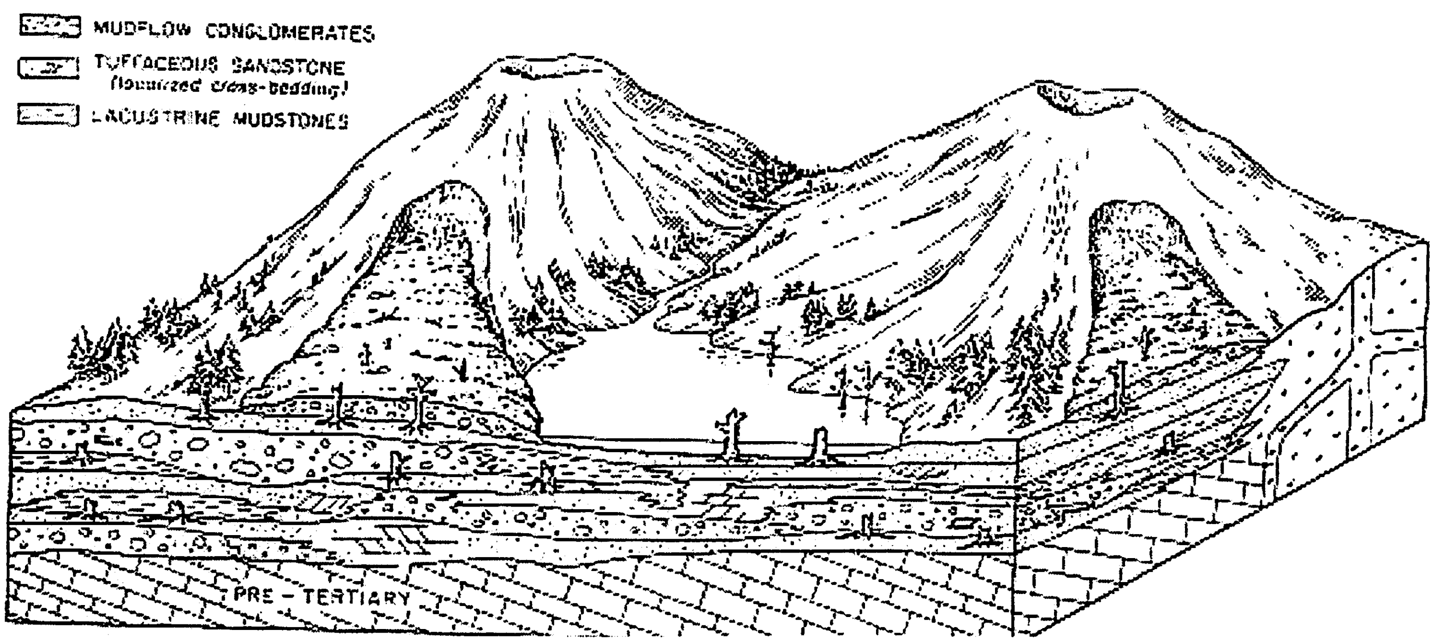


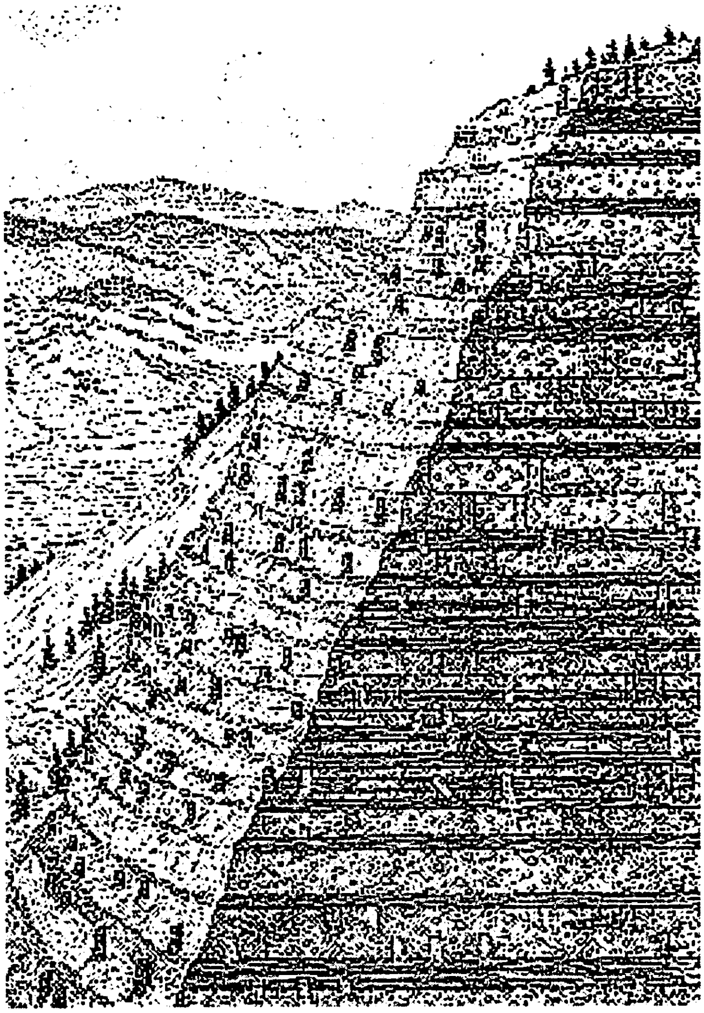
Figure 2: Geologic map of the Lamar River Formation in northern Yellowstone National Park showing sites of measured sections and their relation to Eocene eruptive centers and stylized Eocene topography. Modified from Fritz, 1980a; Tlr from USGS, 1972).

The volcanic eruptions were about 15 miles from the Lamar River valley, shown on the map on the opposite page. The resulting mud flows and landslides drained into the valley. This depositional environment is depicted at the bottom the page (Yuretich, 1984).

At right is a generalized stratigraphic column of the Lamar River Formation (Fritz, 1980) which shows the types, thickness, and prevalence of different materials. The three main sedimentary rocks are: 1) tuffs consisting of fallen ash, 2) breccias with angular fragments deposited by mud flows, 3) conglomerates laid down by streams. Petrified trees are found throughout the different sedimentary materials, but other planet fossils are only contained in the tuffs and shales.





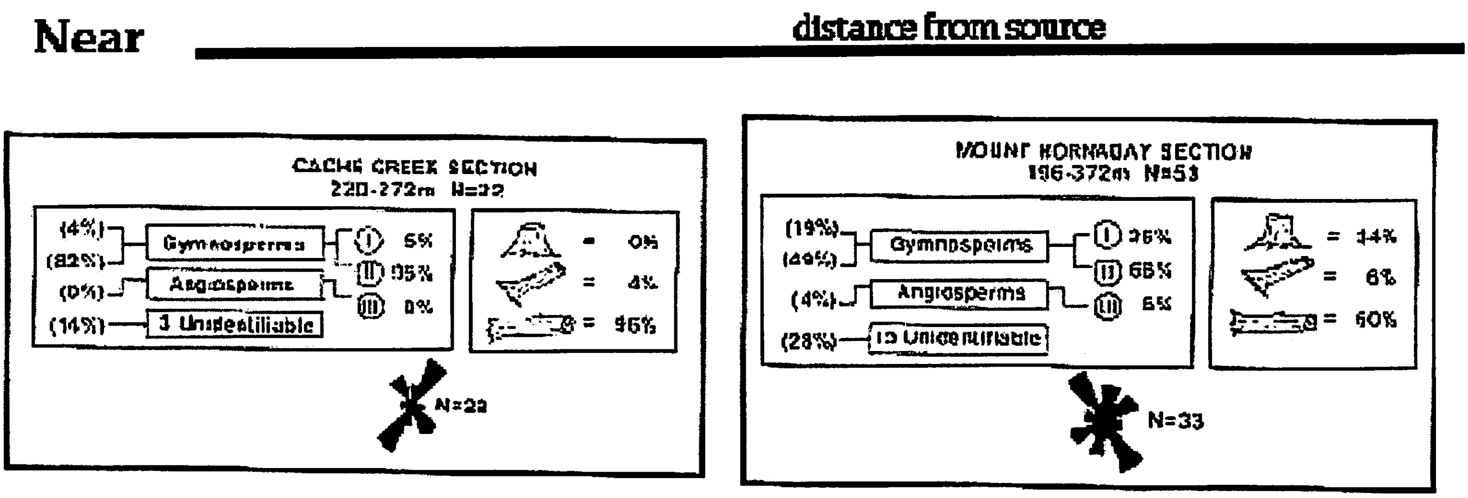


OVER 27 FOSSIL FORESTS: This is a drawing of a portion of the NE slope of Amethyst Mountain which shows the many different layers of petrified trees, each of which, some think, is evidence of a separate eruption event (Dorf, 1964).

Jim Bridger, a famous mountain man, had his own explanation for the fossil forests. In this version, a great Indian medicine man cursed a mountain, dooming everything on it to stand frozen in time: trees, grass, elk, bears, birds in mid-flight, all petrified. Supposedly, even the sun and moon shone with petrified light.

Of course today there is agreement for the general volcanic scenario already described, though when it comes to the details, there are still different versions of the story. Most of the debate has to do with determining the importance of transport by mud flows or other means.

Some feel the presence of tall, upright tree trunks, as shown on the first page, is strong evidence that the forests were buried in place to depths of 10 - 15 ft. Others have examined the roots of these tree trunks and found soil-type structures, further evidence for burial in place. Another study determined the trunks were always rooted in a fine-grained sandstone, not in



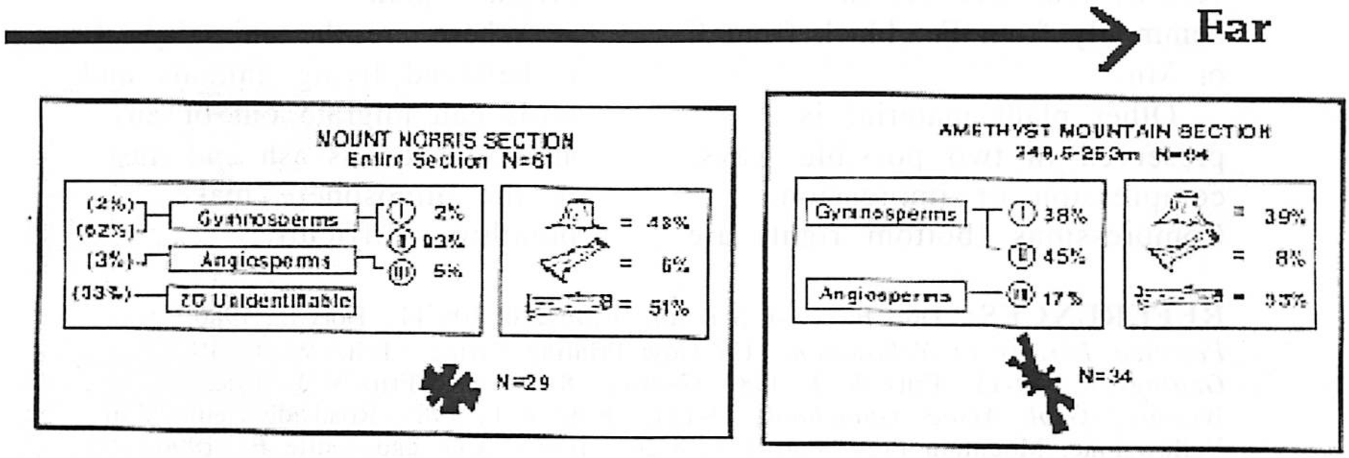
the conglomerates or breccias.

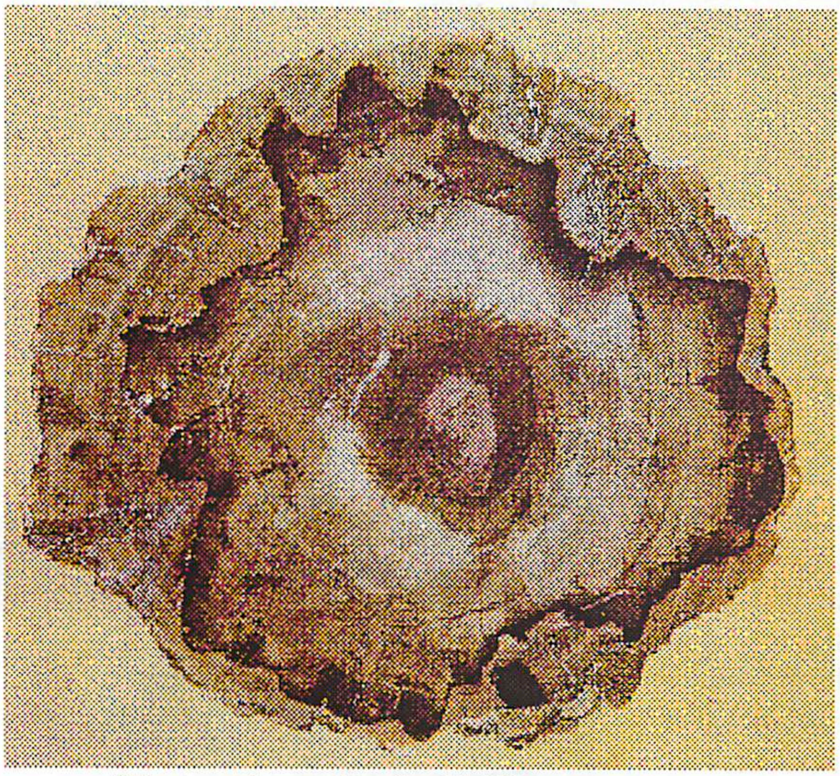
At a location like shown in the drawing to the left, by examining the upright tree trunks, at least 27 separate fossil forest layers were counted. This suggests at least 27 separate volcanic events, with enough time in between for new forests to grow. By counting the growth rings in the trunks, and knowing 200 years after an eruption a new forest can grow, it was calculated that the 1200 ft of buried forests took place in 20,000 years: a rapid rate of 0.7 inches/yr, or 100 times Gulf Coast sediment deposition.

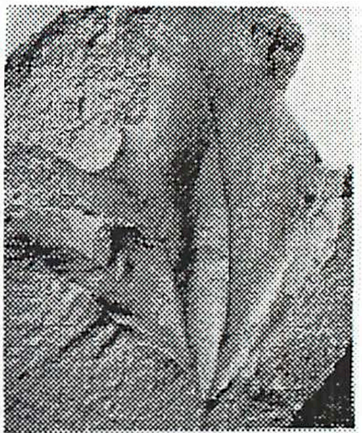
However, others claim the diverse collection of temperate and tropical planets indicates transport was significant. If Mount St. Helens is a modern day analog, short tree trunks with wide root bases can be transported and deposited upright in locations where they never grew, as shown in the picture to the right. Thus, it is argued the depositional environment is complex and layers of distinct volcanically buried forests can not be determined.

By examining the orientation of the trees at various locations, preferred directions were observed, suggesting transport. Also, slight differences with distance from any volcanic source were noted, as shown at the bottom of these pages (Fritz, 1982). Type I and II trees are mostly cool temperate species and type III are mostly tropical.

MOUNT ST. HELENS: Here, a tree trunk has been deposited upright where it never grew: in the middle of a highway. Note the guard rail to the left of the stump.







(Photos from Dorf, 1964)

How Plants are Preserved:

Water, made silica-rich from volcanic ash, permeates the woody tissue, filling the intercellular cavities. The silica is deposited, coating the cell walls and often preserving the original woody structure. Impurities in the silica give color: yellow, red, and brown commonly from Fe; black from C or Mn.

Other plant material is preserved in two possible ways: compression or impression. Compressions (bottom right) are formed by weight from overlying rock layers pressing most of the organic material out, leaving the tough skin of the plant. Impressions (top right) occur in soft surfaces. They usually form negative features, as a mold of the original plant.

Where are the animals? It is believed living animals and birds can migrate out of an area as soon as ash and dust in the atmosphere make breathing difficult.

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The Heart Mountain Thrust Fault

Rachel Mastrapa

Introduction and Snazzy Terms

The Heart Mountain Thrust does not jive with the typical idea of thrusting. It is a very low angle fault, in some places less than 2°. This type of thrust is called a **detachment** or *décollement* (that's French so don't pronounce half of the consonants). Detachments can involve the movement of very large areas of land. In this case the Heart Mountain Thrust Sheet consists of a triangle that's about 30 X 60 miles. A sample of a typical detachment is shown below.

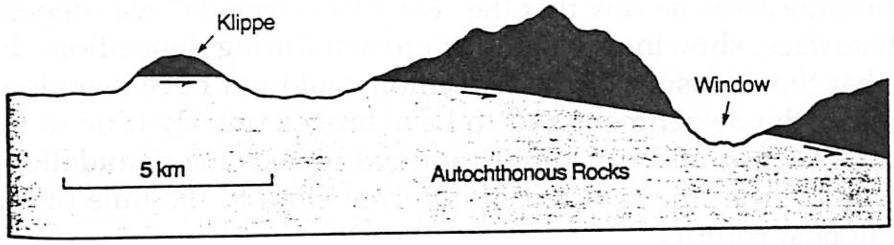

Figure 1

New terms: (skip this part if you've heard of them)

Autochthonous rocks:

The rocks that have not moved. Also referred to as local rocks, or as a group: the autochthon.

Allochthonous rocks:

The rocks that have moved. They make up the thrust sheet. Often referred to wholesale as the allochthon.

***Klippe*::**

Segment of the thrust sheet separated from the rest of the allochthon.

Window (or ***Fenster***):

Section of the autochthon visible at the surface.

Klippes and windows can be formed by either erosion of the allochthon through to the autochton or by a process called **tectonic denudation**. This involves a break up of the allochthon into blocks during faulting.

The Heart Mountain Detachment

In 1957, William Pierce first mapped the Heart Mountain Detachment. His map and cross section are shown in Figure 2. His general breakdown of the fault is as follows. The Heart Mountain consists of four major sections that cover 5 miles. These sections, from north to southeast represent four different kinds of faulting: break away, bedding, shear and erosion. All four sections are shown in an exaggerated scale in Figure 3.

<u>Break Away</u>

This fault cut almost vertically through bedding. The bedding layers affected ranged from the Bighorn Dolomite to the Madison Limetstone (see stratigraphic column, Figure 4).

Bedding

This section of the fault cut parallel to bedding near to but not at the bottom contact of the Bighorn Dolomite.

Shear

This fault cut back up through the bedding layers to the Madison Limestone.

Erosion

This fault placed older material of the Madison Limestone on top of younger deposits ranging in age from the Paleozoic to the Tertiary.

The timing of the fault was determined by Pierce due to observation of volcanic deposits. He noted two different deposits, an "early acid breccia and an "early basic breccia" . In some areas he saw that the "early basic breccia" was deposited directly on the fault surface, showing no signs of erosion during deposition. He therefore concluded that the exposure of the autochton could not have been long in duration. This means that the detachment had to have broken quickly (due to uplift of the Beartooth Mountains), and the klippes formed by tectonic denudation not erosion. Also, this would mean that volcanism occurred close to the time of fault rupture, but definitely post rupture.

Problems and Possible Mechanisms

The following are problems associated with Pierce's model of a catastrophic faulting model, and some possible mechanisms to solve them:

Problems

1. The fault that broke along bedding interpreted as the beginning of rupture is all very low angle and showed no sign of lubrication.
2. The bedding fault also broke along the most resistant bed, i.e. the Bighorn Dolomite. This is especially strange since, just below it is a Cambrian Shale that should have ruptured first.
3. If the fault did rupture quickly, then very high shear stresses had to be involved canceling out a simple gravity model.

Mechanisms (Pierce, 1973)

1. **Fluid Pressure** (Davis, 1965)

   This model is commonly used for deep faulting where high pressure fluids can act a s a lubricant. However, the detachment is a little too shallow for this model to be applicable. However, later studies use evidence of change in the ΔO^{18} along the fault surface that some fluid low had to occur. However, it was probably not due to lithostatic pressure (Templeton, 1995).
2. **Landslides** (Hsu, 1969)

   Since the fault blocks seemed to maintain their original bedding and did not show signs of fracturing or brecciation as would be observed in a landslide, this model was thrown out.
3. **Hovercraft** (Hughes, 1970)

   In this model, volcanic gases are injected into the rock, similar to dike or sill emplacement. This causes the blocks to float downhill like little hovercraft. Unfortunately, though there is evidence for possible gas intrusions in the Northern end of the fault, there is none in the lower section where erosional faulting took place. Later studies have found microbreccia with glass grains that show evidence of fluidization (Buetner, 1996).

4. **Gravity Sliding in Low Viscosity Strata** (Kehle, 1970)
   Sadly, there is no evidence of deformation in the Cambrian shale. Also, deformation is localized close to a thin plane not spread over a large zone.
5. **Earthquake Oscillation** (Pierce, 1963)
   It is possible that a seismic event could act as an acoustic lubrication mechanism. Evidence in support are syntectonic volcanism and fracturing in the autochthon.

The Great Debate or Catastrophism vs. Steady State Change

Once again the oldest disagreement in geology rears its ugly head. People seem to believe that either the land deformed instantaneously or over millions of years, and never the twain shall meet.

In this case, Pierce maintains that his model of tectonic denudation occurred quickly (on a geologic timescale), shown in Figure 5. Conversely, Thomas Hague proposes a continuous allochthon model, which involves repeated faulting of the allochthon including some of the volcanic deposits above it. What it basically comes down to is a disagreement over whether the contact between the volcanic breccia and the autochthon is erosional or no. Thus, the debate rages on.

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Brought to you by the letter R and the number 17.

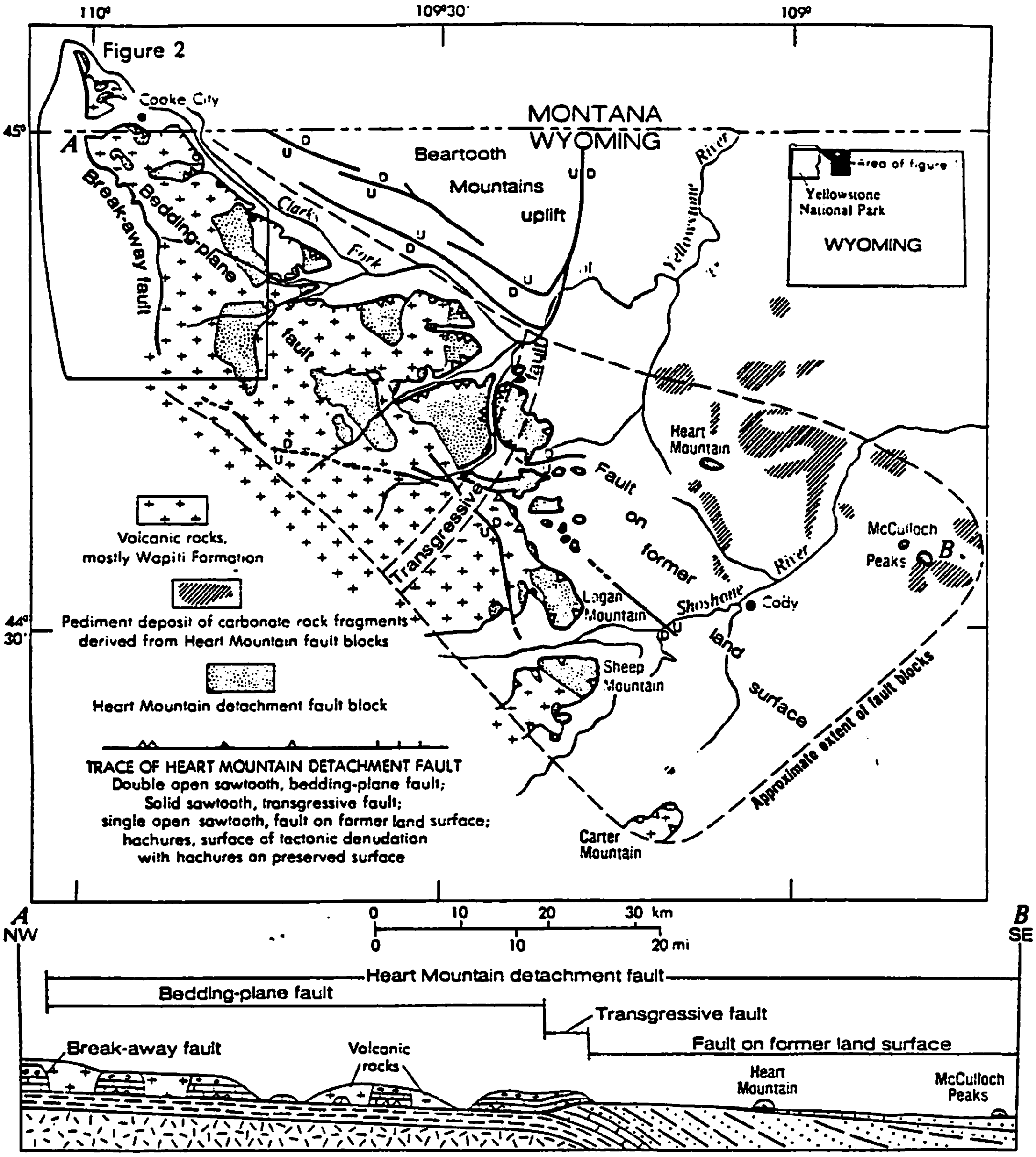


Figure 2

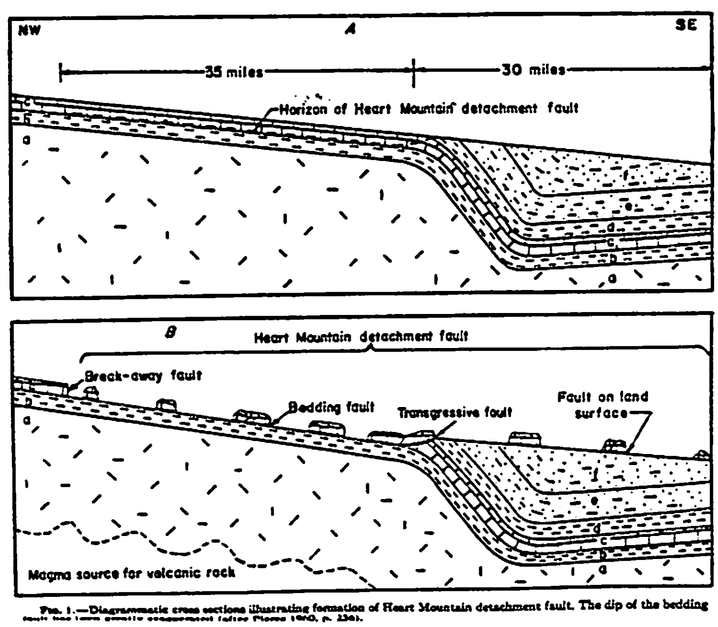


FIG. 1.—Diagrammatic cross sections illustrating formation of Heart Mountain detachment fault. The dip of the bedding [illegible]

Figure 3

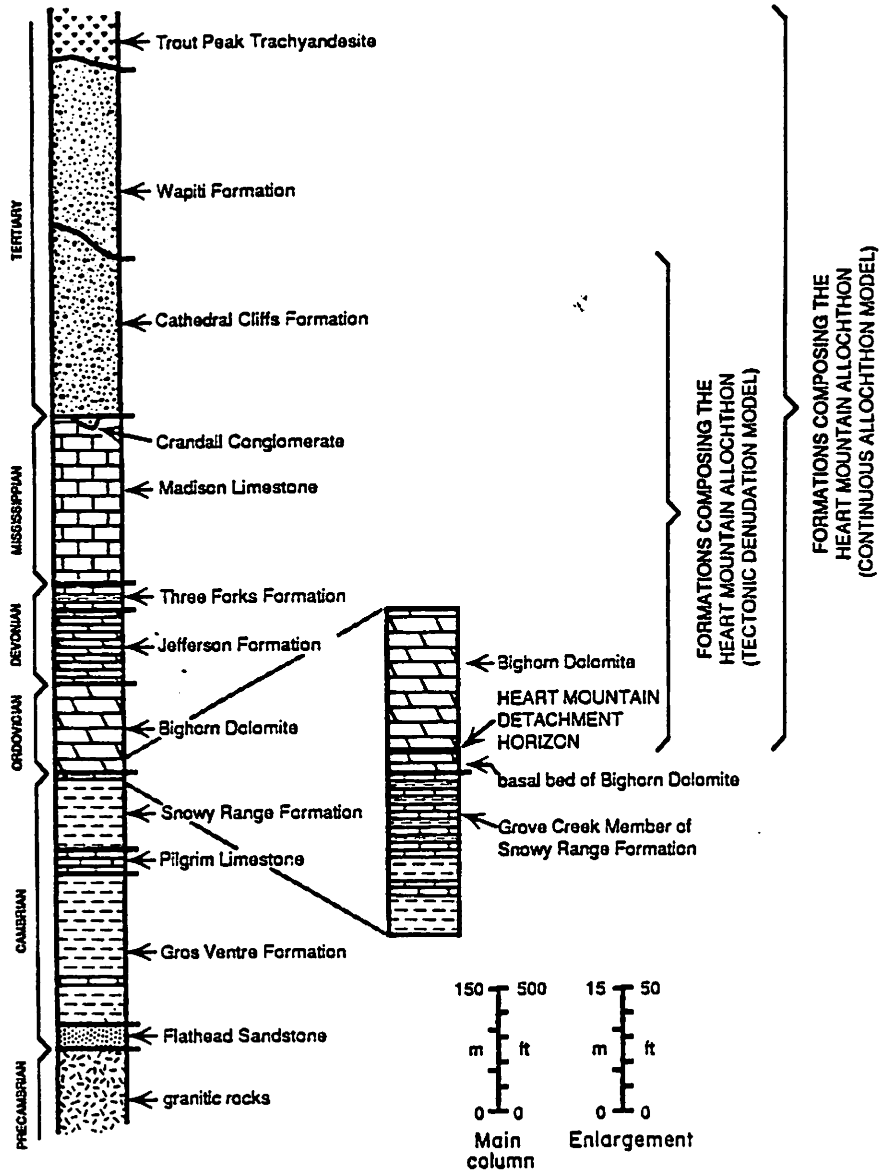


Figure 4

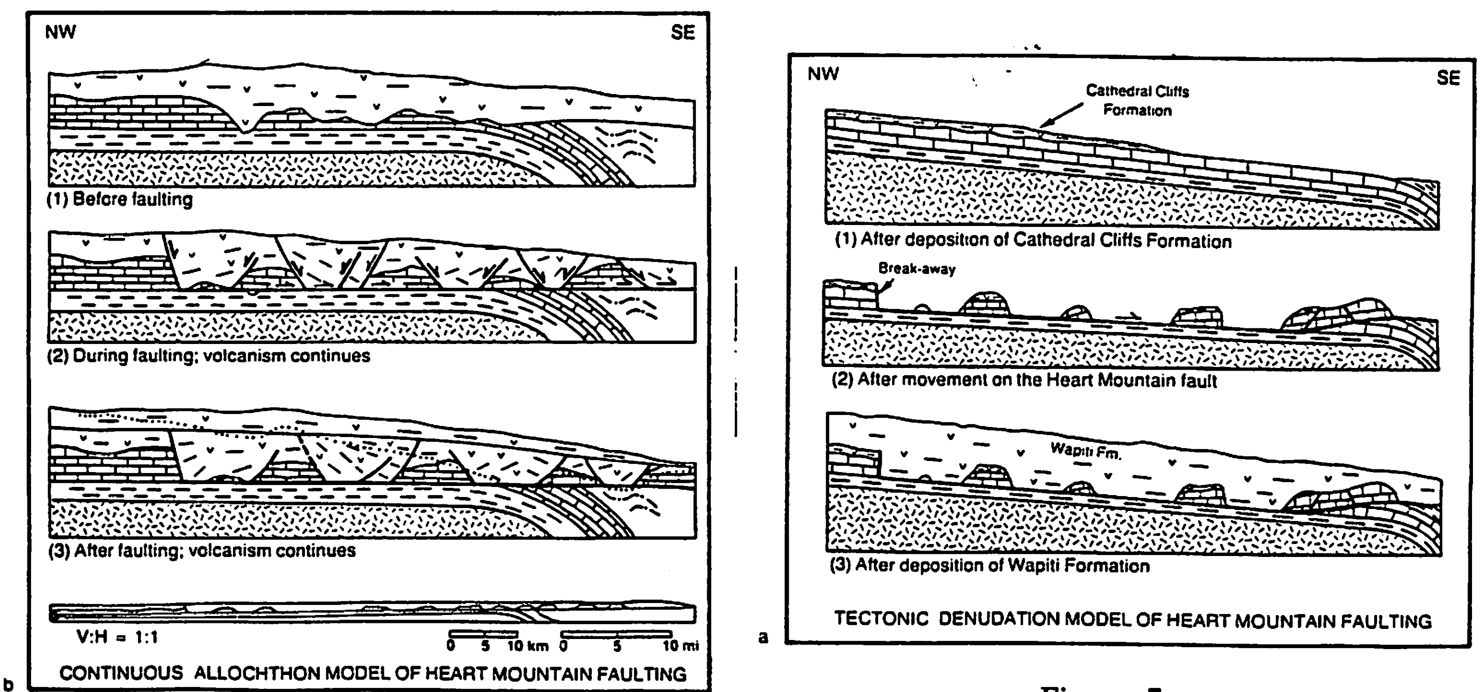


Figure 5

On the Interoceanic Mobility of Freshwater Trout

or

Geology 101: What Makes Water Flow Downstream?

Eric Wegryn

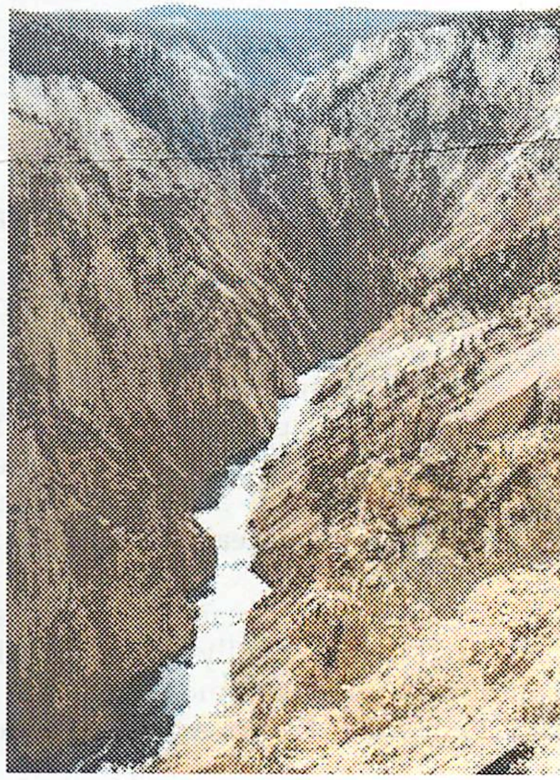
The primary function of rivers (also streams, brooks, cricks, etc.) is to reduce the gravitational potential energy of water in liquid form on the surface of our planet. Although gravity is ubiquitous, and the vertical transport of water is the very *raison d'être* for a river, the shape and solidity of the planetary crust usually necessitates a great deal of *horizontal* motion also on the part of the water.

Rivers and streams thus transport water, mostly horizontally, from higher land to lower (usually as far as the global ocean). The ratio of the vertical component of water motion to the horizontal component is determined by the **riverbed**, and is known as the **gradient**.

Rivers and streams are fed by rainfall and snowmelt, as part of the **hydrological cycle**. But they also carry more than water, of course. The moving water picks up solid material of various sizes (sand grains, pebbles, etc.) from the land, and can carry a certain amount downstream with it. The amount a river can carry (its capacity) is a function of its **discharge** (cross sectional area times flow velocity). In addition to carrying smaller particles, medium-sized particles can be made to hop or **saltate** along the riverbed by the flowing water, and periodic temporary deluges can concentrate more water in a channel, moving fast enough to dislodge still larger rocks and boulders. In this way rivers erode the landscape, and the entire world is being flattened out by fluvial **erosion**. (Although of course there are other competing processes which make it lumpy again.)

As a river erodes the land it is flowing over, it cuts its channel deeper and deeper. The great V-shaped valley of the Grand Canyon of the Yellowstone is a classic example of vigorous downcutting. And in places where part of the underlying rock is particularly strong, waterfalls may form and eventually grow to the magnificent heights of the upper and lower Yellowstone Falls.

When flowing water enters a larger channel (or a lake, or ocean) and slows down, it can no longer support as much sediment as it has been carrying, and some of it settles out to the riverbed (or sea floor). This process of **deposition** (in concert with erosion) continually alters the shape of a river, forming such things as wide meanders, and intricate deltas at the river mouth. In addition, a river may overflow its channel during periodic floods, and deposit a great deal of sediment on the surrounding land when the water recedes, creating a flat **floodplain**. Alternating periods of downcutting and floodplain construction may result in stepped levels called **terraces**.



The Grand Canyon of the Yellowstone

Rivers and streams form large systems, called **drainage basins**, in which many small channels combine into larger and larger channels to carry water to a common destination (a lake, ocean, or, in hot, arid climates, simply to evaporation and oblivion).

A topographic crest which separates one drainage from another is called a **divide**. As an extreme example, the North American continental divide, stretching along the Rocky Mountains, separates water which can only flow into the Atlantic ocean from water which ends up in the Pacific (or the Great Basin).

Yellowstone National Park straddles the continental divide, so rain which falls in the southwestern corner of the park flows into the Snake River, which flows into the Columbia, which flows into the Pacific ocean; while rain that falls to the north or east flows into the Yellowstone River, which flows into the Missouri, which flows into the Mississippi, which flows into the Gulf of Mexico (Atlantic ocean).

However, Yellowstone park, outstanding in so many ways, also contains a rare example of an *indefinite* divide. Near the southern boundary of the park, saddling the continental divide, is Two Ocean Pass, a place where two streams (North Two Ocean and South Two Ocean) come together in a swampy meadow, out of which flow two other streams, Atlantic Creek to the east and Pacific Creek westward. Thus in Yellowstone we have a complete watercourse connecting the Atlantic and Pacific oceans through the midst of the vast North American continent, and it is conceivable that a freshwater trout (sufficiently motivated) could become a transcontinental voyager.

References:
F. Lutgens and E. Tarbuck, *Essentials of Geology*, 1992
P.V. Malocha, *Remedial Geology for Engineers and Astronomers*, 1997
J. Hutton and C. Darwin, "Transcontinental voyages undertaken by highly motivated freshwater trout", *J. Speculative. Geol. & Anim. Behav.* 1871

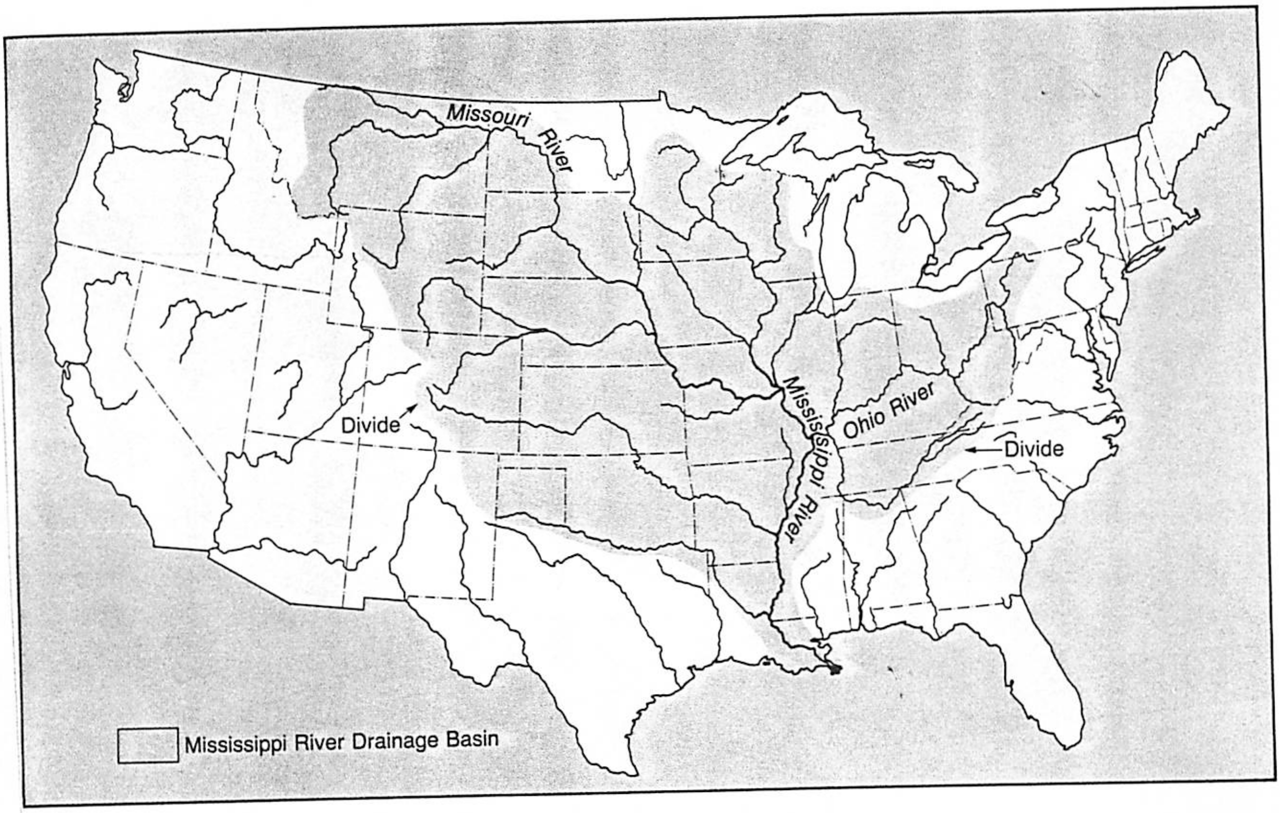


Figure 9.18
The drainage basin of the Mississippi River, North America's largest river, covers about 3 million square kilometers. Divides are the boundaries that separate drainage basins from each other. Drainage basins and divides exist for all streams.

F. Lutgens and E. Tarbuck, *Essentials of Geology,* 1992

The National Park

Eric Wegryn

The combination of extraordinary natural features found in Yellowstone National Park is unique on our planet. It may easily be argued to be the most beautiful or impressive place in the world. In fact, many of its features would be considered worth preserving even individually. But put them all together within a few miles of each other, and it is perhaps inevitable that discovery of such a region by an expanding nation would lead to a revolutionary concept in the preservation of natural features by a government for the people it represents.

The (re)discovery of the Yellowstone region by the new Americans moving westward (mostly by fur trappers and prospectors) led to a slow but sure spreading of unbelievable tales about the geysers and other hydrothermal features. It was not until the exploratory expeditions of Folsom in 1869, Washburn in 1870, and Hayden in 1871 that it was firmly demonstrated that (most of) the stories were true, and that Yellowstone was indeed an area unlike any other on Earth.

As word of the amazing geysers, mud volcanoes, canyons and waterfalls was spread back East (supplemented with photographs by W.H. Jackson and sketches by T. Moran from the Hayden Expedition), support for federal protection of this region began to snowball in size.

Various people have been given credit (and more have claimed it) for the idea of a national park. It was certainly discussed during the Washburn expedition, around a campfire one night at Madison. The men were talking about which parcels of land they would each like to make claims on, when one of them, Cornelius Hedges, suggested that instead of staking claims, they should make an agreement to work toward preservation of the region for all people to enjoy. Seeing the sagacity of this idea, the others quickly agreed.

The idea itself was not without precedent. In 1832, Hot Springs, Arkansas had been designated a U.S. reservation, for the use and enjoyment of the people. In 1864, Yosemite valley, with it stunning glacially carved peaks and waterfalls, was ceded to the State of California for protection. But Yellowstone would be a *national* park (in the Wyoming Territory, it was not then part of any State), and it was this idea of the Federal Government withholding land *indefinitely* from development or exploitation that made Yellowstone the prototype for all future national parks.

So, by an Act of Congress in March 1872, Yellowstone was created the world's first National Park.

The first Superintendent of Yellowstone Park was Nathaniel Langford, who had been part of the Washburn Expedition. But it soon became clear there were serious problems. The act specified administration of the park by the Secretary of the Interior, through the Superintendent, but was woefully lacking in provisions for enforcement of regulations. As a result, the park was nearly destroyed in its first few years through poaching and vandalism (including the soaping of geysers).

In 1886, following a rapid succession of ineffectual superintendents, the U.S. Army was called in to restore order. A fort was established near the present park headquarters at Mammoth, and for the next 30 years, the superintendents were army officers. Military administration proved to be effective but short-sighted, concerned mainly with things like encroachment by the Nez Perce Indians in 1877, and evicting poachers from the park.

In 1890, three new national parks were created in California: Yosemite, Sequoia, and General Grant (later Kings Canyon). Mount Rainier National Park followed in 1899, Crater Lake in 1902, Wind Cave in 1903, and Mesa Verde in 1906. Also at this time, avid outdoorsman and soon-to-be-unemployed President Theodore Roosevelt thumbed his nose at Congress one last time by exercising his power to create 'National Monuments' by presidential proclamation. In the last three years of his term he created no less than nine National Monuments. The family of federally protected parks continued to grow.

Our National Park System came of age in 1916 with the creation of the Department of the Interior's National Park Service. The Army (concerned more about the Great World War than poachers) relinquished control of Yellowstone to civilian administration, and *park rangers* were introduced in the park (although they had already been a feature of the other parks for about ten years).

Since its creation there had often been calls for expansion (and some for contraction) of the area of Yellowstone Park. It was widely agreed that the young and stunning peaks of the Teton range to the south should be protected by the NPS. However, in order to facilitate their passage, bills for modifying Yellowstone's boundaries and for the protection of the Tetons were introduced in Congress separately. Grand Teton National Park was created in 1929, and by 1932 changes had been made to Yellowstone's northern and eastern borders which resulted in a net increase of area to 8983 square km.

In the decades following World War II, as Americans embraced the automobile in ever growing numbers, the National Parks began to see a significant increase in visitors. Roads, bridges, and indeed most of the infrastructure in Yellowstone quickly proved to be outdated, and so a major program of improvement was undertaken in the 1950s and 60s.

In recent years, the NPS has been focusing on preserving a balanced and natural ecology in its parks. The sweeping forest fires in Yellowstone in 1988 have led to a virtual revolution in the handling of natural fires. They are now recognized as an indispensable part of the life cycle of a forest, and most are allowed to burn (unless they threaten human life or property, of course). Another example is the reintroduction of wolves to the park, allowing these predators to coexist with humans and the prey they so enjoy.

The mandate of the National Park Service has always had an air of contradiction about it: to allow and promote access to our nation's greatest natural and cultural treasures, while *at the same time* preserving them for future generations. To this day it continues to walk a fine line between these two goals.

The creation of Yellowstone National Park in 1872 was of course much more than just the preservation of a piece of land for us and our progeny to enjoy. It represented the acceptance of the concept that the land has intrinsic aesthetic value (greater than its monetary value), and was the nascence of an idea that would prove invaluable to nations around the world, that most noble function of government: the preservation and administration of the countryside for people to enjoy simply for its natural wonders.

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A brief chronology of the National Park story:

1832	Hot Springs, Arkansas protected as U.S. reservation
1864	Yosemite valley protected by State of California
1869	Folsom expedition (David Folsom, Charles Cook, & William Peterson)
1870	Washburn expedition (H. Washburn, G. Doane, T. Everts, & others)
1871	First Hayden expedition (F. Hayden, J. Stevenson & others)
1872	Yellowstone created world's first National Park
1886	U.S. Army takes over administration of Yellowstone
1890	Yosemite, Sequoia, and General Grant become National Parks
1908	Teddy Roosevelt creates numerous National Monuments
1916	National Parks Service created; Stephen Mather first director
1929	Grand Teton National Park created; Yellowstone boundaries adjusted
1932	Yellowstone reaches present size and shape
1988	Forest fires ravage much of Yellowstone
1997	More than 350 units in National Park System

Physics of Caldera Resurgence

Vladimir Florinski

Resurgent calderas (or "cauldrons") are characterized by slow uplifting of the floor after their collapse to form resurgent domes. Two other prominent resurgent calderas in the US are the Valles (New Mexico) and Long Valley (California). Common properties of resurgent calderas are:

- Large size (> 10 km in diameter);
- Uplifting is complete after 10^3-10^5 years (closer to 10^3 years in Yellowstone, too short to resolve by the K-Ar method);
- Doming occurs in the centers of the earlier ring fracture systems, created before the major pyroclastic eruption (Fig. 1). The ring fractures are the results of crust inflation or "tumescence" due to the rising magma over an area larger than the resulting caldera;
- Typical magnitudes of uplift are 1-3 km (probably less in Yellowstone); with outward dipping caldera fill;
- Domes are often characterized by distinctive fault patterns, including a keystone graben (across the crest of the dome) — possible sites of future volcanic vents.

Yellowstone caldera has two low resurgent domes formed 600,000 years ago within each of the caldera segment. Mallard Lake dome was covered with rhyolites after the postcaldera ring-fracture volcanism 150,000 years ago.

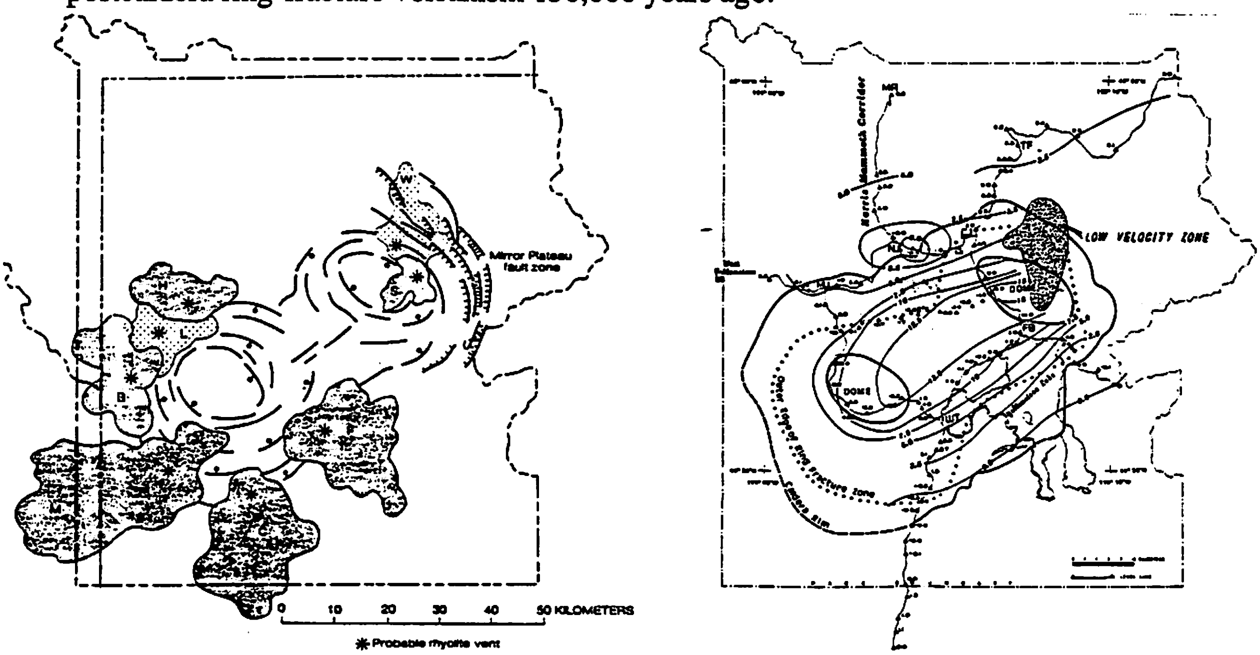

Figure 1. Pre- and post-caldera volcanism in the Yellowstone National Park. Left plot shows the ring fracture systems while the right plot shows locations of resurgent domes and the contours of the current uplift (from Christiansen, 1984 *and* Smith and Braile, 1984*).*

It is difficult to argue that the ultimate source of resurgent doming is the pressure increase in the magma chamber below the collapsed cauldron block. This block usually has thickness of only a few km, thickness to diameter ratio determines the magnitude of the uplift. There are three possible sources of magma resurgence: hydrostatic rebound, regional detumescence and increase in magma pressure due to vesiculation or addition of new magma.

1. Viscous hydrostatic rebound.

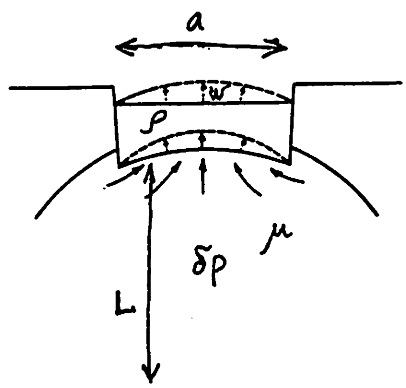

Figure 2.
w — magnitude of the uplift
a — caldera size,
L — height of the magma column,
δp — less pressure in the column,
μ — magma viscosity,
ρ — density of the lid.

The preceding explosive eruption may have emptied the chamber of more magma than is sufficient to maintain hydrostatic equilibrium. The latter must be restored by the upflow of magma. Suppose the pressure in the chamber is less than the surrounding pressure by δp. To restore the balance the block must travel a distance w, such that $\delta p \approx \rho g w$. The pressure gradient $\delta p/L$ drives the magma upward with a characteristic velocity $u \approx -a^2 \delta p/(4\mu L)$ (TS p. 238). Hence,

$$\frac{dw}{dt} = -\frac{a^2 \rho g w}{4\mu L}$$

and a resurgence time is $T_{hr} \sim 4\mu L/(a^2 \rho g)$. With $\mu = 10^7$ Pa s, $L \sim a = 10$ km, $\rho = 2.5\times10^3$ kg m^{-3}, $T_{hr} < 1$ s. This is clearly much too small. However, the block itself might slow down the resurgence by being welded to the surrounding crust at the edges.

2. Regional detumescence.

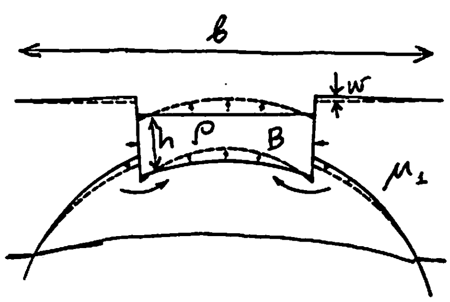

Figure 3.
w — magnitude of the subsidence,
b — tumescence size,
$B = E/(1-\nu^2)$ — flexural rigidity of the lid,
μ_1 — crust viscosity,
h — lid thickness,
ρ — density of the lid.

Detumescence is the effect of relaxation of the crust surrounding the caldera after a period of inflation before caldera formation. As the roof of the magma chamber is lowered, pressure buildup drives the magma up through the cauldron block. For simplicity, consider a thin elastic plate (lid) on top of a highly viscous half-space (crust). For the subsidence of the initial sinusoidal bulge $w \sim sin(2\pi x/b)$ we can write (similar to TS p. 115, but with the load q derived from the deflection of the viscous medium)

$$-\frac{4\pi\mu_1}{b}\frac{\partial w}{\partial t} = \frac{1}{12}Bh^3\frac{\partial^4 w}{\partial x^4} + \rho g w$$

Solution yields relaxation time $T_{dt} \sim \mu_l/[(2\pi)^3/12\ B\ (h/b)^3 + \rho g b/(2\pi)]$. Magma properties have no effect on this result! If $\mu_l=10^{21}$ Pa s, $B= 3.5\times10^{11}$ N m^{-2}, h=5 km and b=100 km, then $T_{dt} \sim 5\times10^4$ yrs.

3. Pressure against the caldera block.

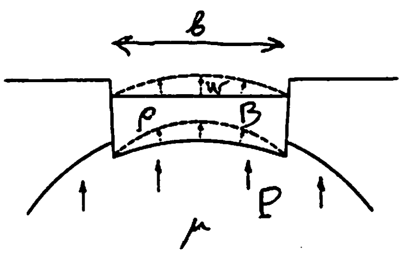

Figure 4.
w — magnitude of the uplift,
b — caldera size,
$B=E/(1-\nu^2)$ — flexural rigidity of the lid,
μ — magma viscosity,
h — lid thickness,
ρ — density of the lid,
P — magma pressure

Buildup of pressure in the magma chamber may be caused by either convection, vesiculation or inflow of new magma. Mathematically this case is similar to the previous one and it can be shown that the uplift time in this case is $T_{mp} \sim 2\mu/[(2\pi)^3/12\ B\ (h/b)^3 + \rho g b/(2\pi)]$. For $\mu=10^7$ Pa s, $B= 3.5\times10^{11}$ N m^{-2}, h=5 km and b=50 km, we get $T_{mp} << 1$ s. But it is possible to get long resurgence times if the magma has partially solidified to increase viscosity to 10^{16}-10^{18} Pa s. Latent vesiculation (exsolution of water from the rising magma as its pressure drops below saturation) appears to be the most likely mechanism for the pressure increase.

Because small calderas have longer resurgence times, their magma chambers may solidify faster, in which case uplifting will never occur. The critical caldera size is estimated to be about 10 km if resurgence is driven by detumescence.

From the previous discussion it follows that each of the possible resurgence mechanisms involve highly viscous upper crust. The previous models are able to predict the uplift magnitude to be 1-3 km. Smaller uplift may be attributed to high degree of fracturing of the cauldron block (magma can escape), but this is not the case in Yellowstone where the central blocks are well preserved. It can be also due to low magma viscosity and large thickness of the caldera block.

In our time, part of the crust under the Yellowstone Caldera is composed of material exhibiting plastic behavior as revealed by seismic velocity measurements (Fig. 2). It is known that the caldera underwent uplifts and subsidence during the past few thousand years as recorded by the position and tilt of Yellowstone Lake terraces. Such data indicate average uplifts of the order of 10 m over a few thousand years. Current rate of uplift/subsidence is of the order of 15 mm/yr. It may be due to periodic accumulation of magma at the top of the crystallizing chamber or episodic addition of new magma to the chamber.

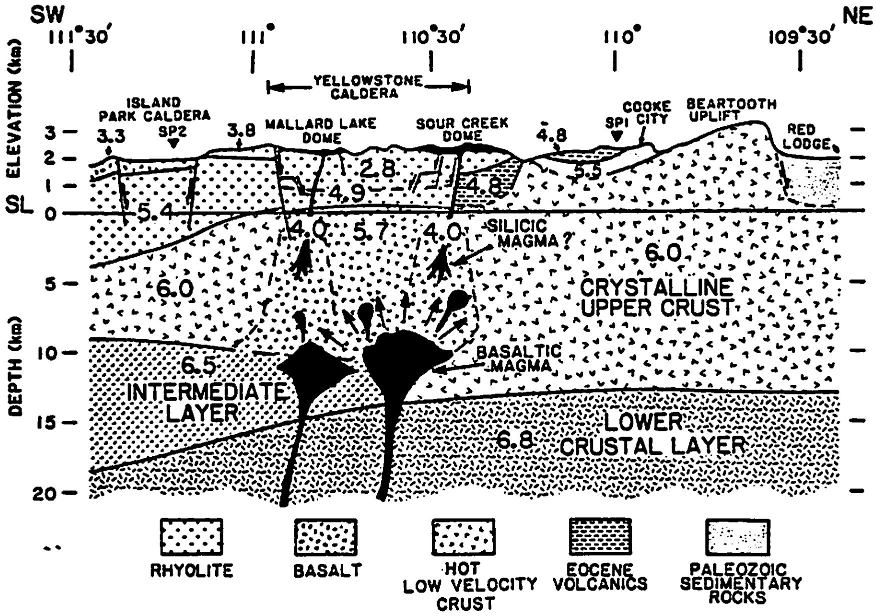

Figure 5. Structure of the crust under the Yellowstone Park deduced from the seismic velocity measurements (from Smith and Braile, 1984*).*

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Geochemistry of Thermal Waters in Yellowstone National Park

conducted by James N Head
September 1997

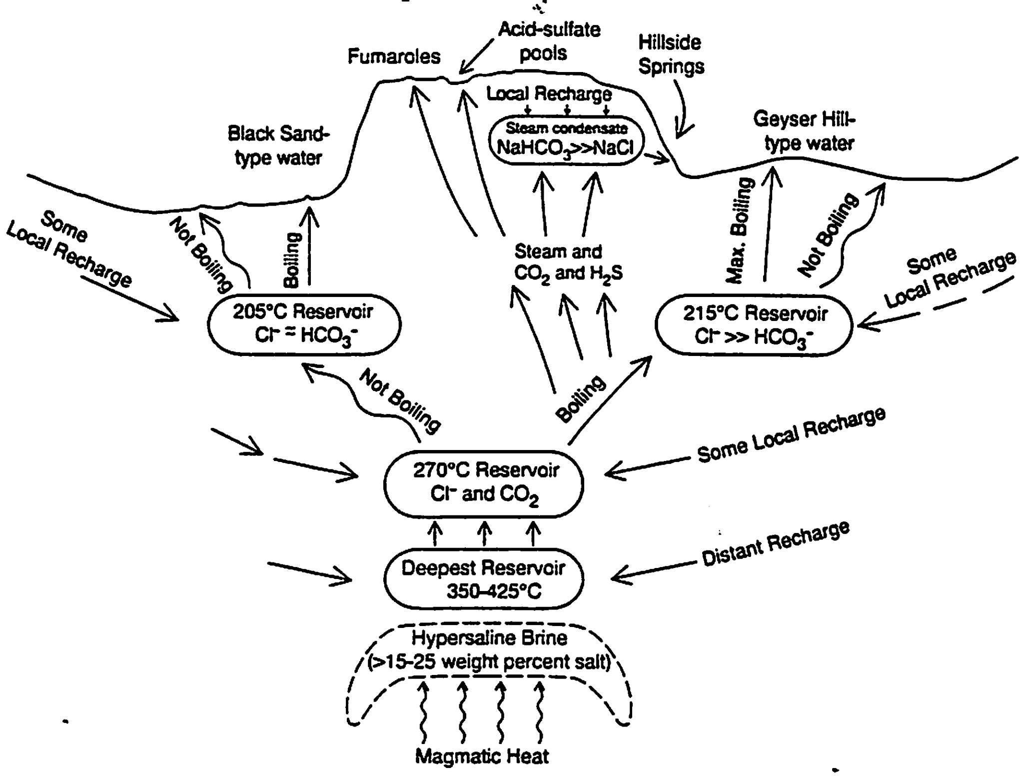


Figure 1

Introduction

The subject of Yellowstone thermal water's geochemistry is rich and diverse. The published literature on this topic goes back to 1888. Only the barest outline is presented herein. The hydrothermal system itself is approximately 4-5km deep and is largely recharged with meteoric waters (Figure 1). Comparison of stable isotopes indicates that magmatic water contributes less than 0.5% of the water volume in the system. The most likely source of recharge is from mountainous areas to the north and northwest of the caldera, where deep snows accumulate (Fournier 1989).

Fluid-Rock Interactions

The residence times for water in the Yellowstone hydrothermal system (months to years) is long enough for the waters to equilibrate chemically with the surrounding rock (Fournier 1981). The composition of the thermal waters depends on the availability and solubilities of salts leached from wall rocks, anions contributed from the influx of acid gases (mainly CO_2), and a deep brine of magmatic origin (Figure 1). For example, the thermal waters at Mammoth Springs flow through sedimentary rock and are rich in bicarbonate and sulfate, in contrast to much of the rest of the thermal waters in the Park, which flow through rhyolites and are chloride-rich (Table 1). However, lead isotope data (of geyser deposits) indicates that all the thermal waters in YNP have been in contact with sedimentary rock. At high temperatures, the effect of rock type is greatly diminished (Fournier 1989). This counter-intuitive result has been confirmed in laboratory experiments (Biscoff and Rosenbauer). The composition of the thermal waters indicates equilibration with rhyolites over a temperature range of 160-350°C. While changes in the behavior of individual geysers and hot springs are common, there has been no significant change in the range of water compositions exhibited by these features for at least a century, and probably much longer (Fournier 1989).

The hydrothermal activity in the western half of the park are typical of hot-water systems (described below). All of the major geyser basins (except Norris and Heart Lake) lie within the part of the 0.6Ma caldera that overlaps the 2.0Ma caldera. The underlying rock is probably relatively permeable rhyolite interbedded with relatively impermeable ash-flow tuffs. Thus there are relatively permeable rhyolite flows of uniform composition that can serve as fluid reservoirs at various depths .

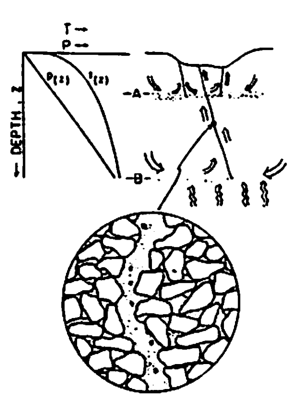
In the eastern part of the 0.6Ma caldera (where it does not overlap the 2.0Ma caldera) most of the caldera fill is likely to be impermeable ash-flow tuffs. In this part of the caldera, vapour-dominated systems are prevalent.

Hot-Water Systems

In hot-water systems the fluid pressure steadily increases downward and the maximum attainable temperature at a given depth is given by the boiling-point curve based on hydrostatic conditions (Figure 2). The typical expression of hot-water systems is a boiling hot spring with possible geyser activity. The waters are mostly slightly alkaline and chloride-rich. Examples include the Upper, Midway, Lower, West Thumb and Shoshone Basins inside the 0.6Ma caldera and Norris and Heart Lake Basins outside (Table 1, 2-6). However, acid-sulfate boiling pools with little discharge of water can occur in geyser basins (Table 1, 7). In these cases the liquid water fraction separates and emerges as a boiling spring in topographic lows. The steam fraction contains H_2S that oxidizes to H_2SO_4 on contact with air in perched pools of groundwater. Examples are Iron Spring in Upper Geyser Basin, the Fountain Paint Pot in Lower Geyser Basin, and the Thumb Paint Pots at West Thumb. The waters at Mammoth Hot Springs are rich in Ca and Mg, reflecting the prevalence of sedimentary rocks in the reservoir.

Vapour-Dominated Systems

In vapour-dominated systems, steam and other gases (mainly CO_2 and H_2S) fill open fractures beneath a cap that acts as a throttle, with liquid water mostly in the pore spaces (Figure 3). Typical expression of these systems are fumaroles, acid-boiling pools with little discharge of water, mud pots, and the absence of alkali-chloride-rich waters (Table 1, 8). The rising steam carries volatile gases (CO_2, H_2S, NH_3, Hg, B) toward the surface and leaves non-volatile components (e.g., Cl) behind. At Yellowstone, the steam appears to separate at 5-15 bars, corresponding to 150-200°C. The steam may condense and react with wall rock, resulting in a solution rich in bicarbonate, poor in chlorine, poor in sulfate (little oxygen to convert the H_2S). An example is in Table 1 (9). Some hot springs are rich in methane, ethane and ammonia derived from buried sediments. Distillation at high temperature and pressure results in a steam where $NH_3 > H_2S$. When the steam condenses, the H_2S is oxidized to sulfuric acid, which is converted to ammonium sulfate by the excess NH_3 (Table 1, 10). Elsewhere, condensing steam results in high bicarbonate-low chloride waters such as in the Hillside group (Figure 1).



← Figure 2

Figure 3 →

Figure 4.14. Schematic model of conditions in a hot-water-dominated geothermal system where boiling temperatures prevail through a steeply dipping structure filled with water

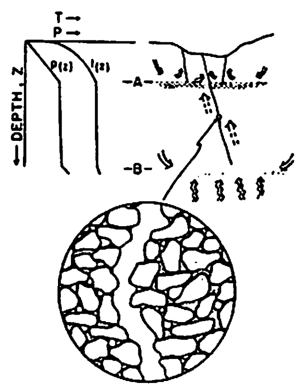


Figure 4.13. Schematic model of conditions in a vapor-dominated geothermal system

Table 1
Chemical composition of Yellowstone hydrothermal waters (with comparison data).

Basin	1 M	2 WT	3 Sh	4 LB	5 UB	6 NB	7 FeSpg	8 HS	9 JC	10 Wsh	11 SW	12 SP	13 UA
T(C)	70	90	81	95	94	94	91	89	94	91	20	30	20
pH	7.5	7.8	9.0	7.7	8.3	-	3.7	2.7	9.4	8.0	7.4	7	7
SiO_2	88	-	328	230	312	654	365	317	238	247	3	-	-
Ca	450	2.0	0.4	0.75	0.67	2.12	2	37.1	3.4	2	400	300	-
Mg	80	0.51	0.05	0.01	0.02	0.03	tr	3.75	0.01	4.1	1350	*	-
Na	161	408	365	330	420	404	77	187	109	9.7	10500	**	**
K	69	20	16	10	17	81	28	16	19	6.5	380	**	**
NH_4	1.0	-	0.1	-	-	-	4	171	22.4	270	-	-	-
HCO_3	997	531	406	246	590	47	0	0	335	107	-	120	0.88
SO_4	800	55	48	26	19	31	231	1530	24	900	885#	-	70
Cl	171	261	328	326	289	669	1	0.1	5.4	7	19000	2	<0.2
F	4.2	14.5	25.5	30	28	5.8	1.2	0.8	3.7	0.1	1.3	-	0.7

All concentrations are given in mg/kg (ppm). The sampling sites are M-Mammoth, WT-West Thumb, Sh-Shoshone, LB-Lower Basin, UB-Upper Basin, NB-Norris Basin, FeSpg-Upper Basin Iron Springs, HS-Hot Springs Basin, JC-Joseph Coats, Wsh-Washburn Hot Springs, SW-Sea Water, SP-Swimming Pool, UA-University of Arizona Drinking Water. YNP data from Fournier (1989). Sea water data from Handbook of Chemistry and Physics, CRC Press, 1984. Swimming pool data provided by Leslie's Swimming Pool Supplies, Tucson. Drinking water data courtesy Bill Witschi, University of Arizona.

*Included in Ca data.
**Included in HCO_3 data.
#Includes all S not in sulfate.

Table 2
The pH of common substances.

stomach acid	1.2
lemon juice	2.4
vinegar	2.9
sauerkraut	3.7
urine	4.9-8.1
saliva	6.5-7.8
milk	6.7
milk of magnesia	10.6

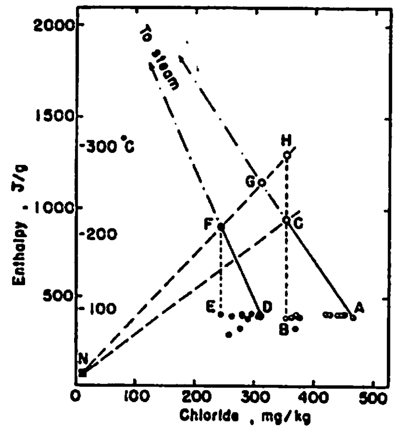


Figure 4.12. Enthalpy-chloride relations for waters from Upper Basin Yellowstone National Park. Small circles indicate Geyser Hill-type waters and small dots indicate Black Sand-type waters

Figure 4

Reservoir Temperatures (adapted from Fournier, 1981)

Geothermometers are used to recover the temperature history of thermal waters. They take advantage of the temperature dependence of equilibrium constants in exchange reactions. As an example

$$\underset{\text{Albite}}{NaAlSi_3O_8} + K^+ = \underset{\text{K-feldspar}}{KAlSi_3O_8} + Na^+$$

$$K_{eq} = [Na^+]/[K^+]$$

A single equation is hardly sufficient in real rocks of course, where one must account for quartz, micas, and clay minerals. This is discussed in detail in Fournier (1981). The most widely used geothermometers are silica, Na/K, Na-K-Ca, $\delta^{18}O$, and chloride.

Silica. The silica geothermometer works best for waters between 150°C and 200°C. The method depends on the temperature-dependent solubility of various silica phases. Steam separation increases the concentration of silica, therefore corrections must be made for the proportion of adiabatic vs. conductive cooling. Precipitation of silica both before and after sample collection must be compensated for or prevented. pH also effects the results.

Na/K. Works best for T>180-200°C. The main advantage is that Na/K is robust against dilution or steam separation compared to other geothermometers. Low temperature waters rich in Ca give anomalous results.

Na-K-Ca. Developed specifically to deal with Ca-rich waters where the Na/K method fails. Under some conditions must be corrected for Mg concentration.

$\Delta^{18}O(SO_4\text{-}H_2O)$. This depends on the temperature-dependent partitioning of ^{18}O between sulfate and water. Once the equilibrium is established, there is little re-equilibration of the oxygen isotopes as the water cools. Boiling makes use of this method more complex.

Enthalpy-Chloride. Enthalpy chloride diagrams can be used to estimate the reservoir temperature (Figure 4). When a range of chloride concentrations results from differences in boiling, that range can provide a minimum temperature for the reservoir feeding the spring. The reservoir temperature for Geyser Hill waters is calculated by drawing a line from Point A (highest chloride concentration, presumably has experienced the most boiling) to the enthalpy of steam at 100°C. Then extend a vertical from Point B (lowest chloride concentration, presumably has experienced no boiling). The intersection (Point C) gives a reservoir temperature of 218°C. The silica thermometer applied to A (maximum boiling) gives 216°C, and silica applied to B (no boiling) gives 217°C. The agreement between chloride and silica thermometers is strong evidence the reservoir feeding Geyser Hill is about 218°C. The same exercise is illustrated for Black Sand waters, which gives a temperature of 209°C by chloride and 205°C by silica. Waters C and F cannot be related by dilution with cool ground water– such a mixture would lie close to line CN. Both can be related to G, however: C by boiling and F by dilution. This scenario explains why the Black Sands water (F) has a lower $Cl/HCO_3 + CO_3)$ value, since Geyser Hills would lose CO_2 during boiling. Using additional data from Midway and Lower Basins, Fournier *et al.* (1976) have concluded that a reservoir at ~270°C underlies the Upper and Lower Basins and that a still hotter reservoir resides at greater depth (Figure 5, *n.b.* the axes are reversed from Figure 4).

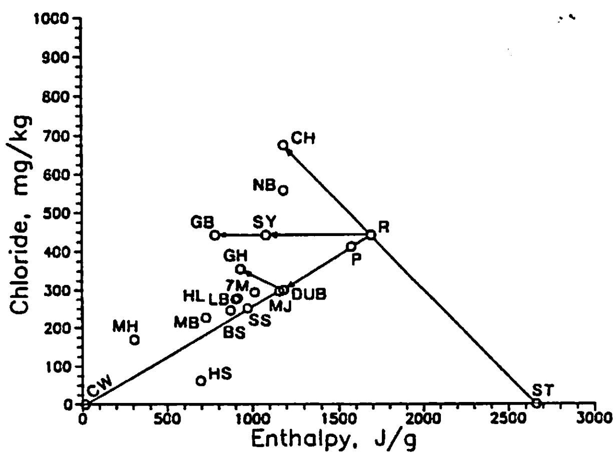


Figure 5 Enthalpy of liquid water vs. chloride for various aquifers. Letter codes as follows: 7M, Sevenmile Hole; BS, Black Sand-type water; CH, Crater Hills; CW, cold water; DUB, deep Upper Basin 270 C water; GB, Gibbon; GH, Geyser Hill type water; HL, Heart Lake Basin; HS, Hillside Springs; LB, Lower Basin high chloride/bicarbonate water; MB, Midway Basin; MH, Mammoth Hot Springs; MJ, Madison Junction; NB, Norris Basin; P, the deep parent water of Fournier et al (1976); R, deepest and hottest reservoir fluid; SS, Shoshone Basin high-chloride water; ST, steam; SY, Sylvan Springs.

Convective Heat Flux

The convective heat flux of the Yellowstone hydrothermal system can be estimated using the chlorine abundances in the deep reservoir and in the streams draining the Park. The concentration of Cl- in the streams, after correction for runoff, indicates the mass of water brought up from depth. Along with the temperature of the deepest, hottest reservoir, one calculates a total heat transport of 5.3×10^9W. This quantity of heat is equivalent to the crystallization of 0.2km^3 of rhyolitic magma per year. Over the area of the Yellowstone caldera the convective heat flux is 2000mW/m^2, comparable to the calculated heat flux for Io.

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A note about the Figures:

Figure 1 is from Fournier *et al.* 1994.
Figures 2,3, and 4 are from Fournier 1981.
Figure 5 is from Fournier 1989.

Yellowstone Caldera

Janet McLarty

Yellowstone caldera is the youngest of a string of calderas that have formed over a hotspot that is now under Yellowstone National Park (see Appendix A). This paper will discuss the formation and evolution of resurgent calderas in general and will then discuss the particulars of the formation and evolution of Yellowstone caldera.

Formation and Evolution of a Resurgent Caldera

A *caldera*, the Spanish word for cauldron, is a basin-shaped volcanic depression that, by definition, is at least one mile in diameter. A *resurgent caldera* is an extremely large caldera that shows post-eruption upheaval (resurgence) of its floor. Resurgent calderas are therefore characterized by broad topographical depressions with central elevated massifs.

The formation of a resurgent caldera starts with the formation of a large magma chamber deep within the earth. The magma then slowly forces its way toward the surface. As it pushes upwards, it arches the overlying rocks into a broad dome which produces a series of concentric, or ring, fractures around the crest of the dome. These fractures extended downward toward the top of the magma chamber. Small amounts of lava start to flow through the cracks.

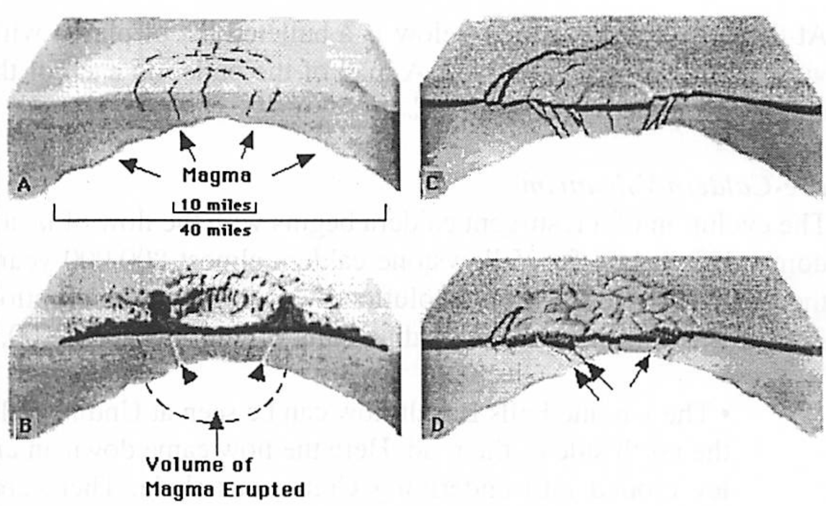


FIGURE 1: A. The magma chamber causes doming and ring fractures. B. The fractures hit the magma chamber and the ash flows out. C. Collapse causes a caldera. D. Post-caldera formation flows fill in the caldera. (Keefer 1976)

The ring fractures eventually reach the top of the large magma chamber, which contains a high proportion of dissolved gases. ith the sudden release of pressure, large amounts of gas and molten rock erupt explosi ely. The lava solidifies to pumice, ash, and dust as it is blown out at huge rates and high velocities. Some of the debris is carried by the wind to distant places, but most of it moves in enormous ash flows to cover the surrounding terrain.

Once the magma chamber has emptied, the rock above it collapses to form a giant caldera. Molten rock then rises again and seeps out through the fractures surrounding the ring fracture zone. These lava flows spread across the caldera floor. The rising molten rock again domes the caldera floor abo e the magma chamber.

The Yellowstone Caldera

The Yellowstone caldera is the youngest of three resurgent calderas in Yellowstone National Park. The oldest formed approximately 2.0 Ma and is associated with the Huckleberry Ridge Tuff. This caldera is huge, and the younger calderas sit mostly within it. The next caldera is the Henry's Fork caldera in the southwest portion of the older caldera. The Henry's Fork caldera formed approximately 1.3 Ma and is associated with the Mesa Falls Tuff. (See Appendices.) The youngest caldera is the Yellowstone caldera, situated in the eastern portion of the ancient caldera, and it is the caldera that the rest of this section will focus on.

This process of formation and evolution of a resurgent caldera can be broken down into five stages:

1. Pre-Caldera Volcanism
2. Eruption of Pyroclastic Rocks
3. Caldera Formation
4. Post-Caldera Lava Extrusion
5. Resurgence

At the end of each section below is a bulleted list of places within Yellowstone National park to view the landforms discussed. A map of the park and each of the listed places is provided at the end of this paper-in Appendix C.

Pre-Caldera Volcanism

The evolution of a resurgent caldera begins with the flow of lava through cracks around a growing dome. This began for Yellowstone caldera almost 800,000 years ago (about 500,000 years after the end of the Henrys Fork evolutionary cycle) with the eruption of the Mount Jackson Rhyolite flo . It was followed by the Undine Falls Basalt flow about 100,000 years later.

- The Undine Falls Basalt flow can be seen at Undine Falls, 4.5 miles east of Mammoth on the north side of the road. Here the flow came down an ancient stream bed and filled a valley eroded into underlying Cretaceous shale. There are 3 waterfalls that flow over the basalt which exist because the stream does not erode the basalt as fast as it erodes the shale.

Eruption of Pyroclastic Rocks

When the ring fractures hit the two large magma chambers beneath the dome 600,000 years ago, a huge amount of debris was thrown to the surface. Over 240 cubic miles of ash and basaltic flows erupted to cover the surface and to clog the air. (For comparison, Mt. St. Helens erupted less than 0.5 cubic miles of ash.) The ash was thrown as far away as Louisiana, while the welded-ash flows went for miles in all directions. The ash flows came so quickly that they cooled into one unit known as the Lava Creek Tuff.

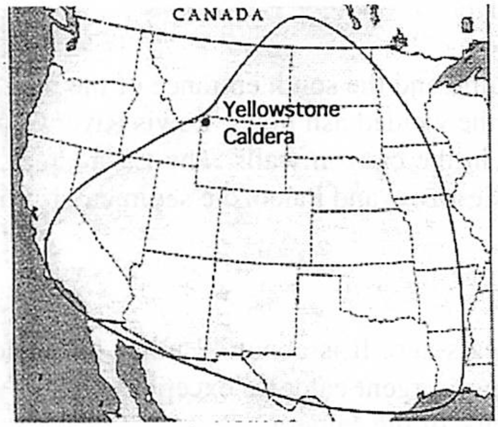


FIGURE 2: Distribution of ash fall from Yellowstone Caldera. Mapping largely done by G.A. Izett and his colleagues at USGS. (Francis 1993)

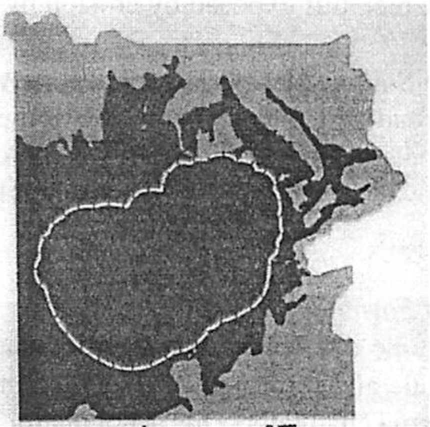


FIGURE 3: Original extent of Lava Creek Tuff flows. Yellowstone Caldera is outlined. (Keefer 1976)

The Lava Creek Tuff can be seen at many places throughout the park. A few good places to look are listed below.

- The Tuff Cliff east of Madison Junction is an air-fall welded-ash deposit. In figure 4, the Gibbon River, the road and the tuff are all outside the northern caldera rim. To the right (or south) of the River, less than one mile away, sits the northern caldera rim buried under rhyolite flows.

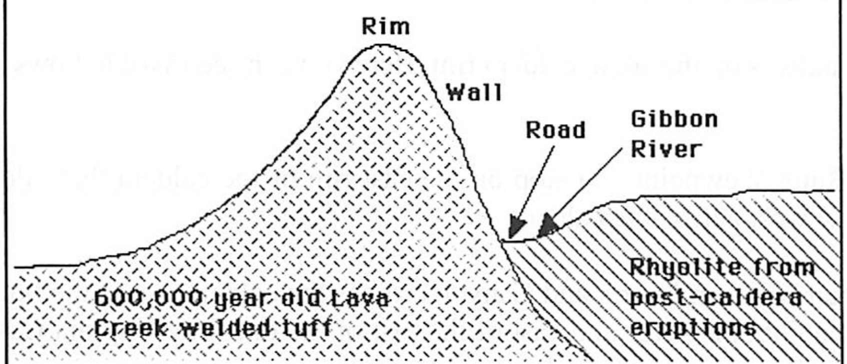


FIGURE 4: Geology of the tuff cliff region east of Madison Junction. (Keefer 1976)

- Gibbon canyon, east of the tuff cliff and between Madison Junction and Norris, exposes the Lava Creek tuff on the north and west sides. The east wall is a younger plateau rhyolite.

- Wraith Falls, 5.5 miles east of Mammoth on the south side of the road, exposes the Lava Creek tuff.

- Virginia Cascades, east of Norris on the south side of the road, gives a view of the Lava Creek tuff exposed by erosion by the Gibbon River.

- South of Lewis River Falls, between West Thumb and the south entrance of the park, the road descends from the rim of the caldera onto the welded ash flows. Lewis River Canyon cuts through and exposes some of these flows in the canyon walls. The Lava Creek tuff overlies older rhyolite flows that lie on buried Mesozoic and Paleozoic sedimentary rocks.

Caldera Formation

Yellowstone caldera formed approximately 600,000 years ago. It is about 47 miles long and 28 miles wide and it formed as discussed in the section on resurgent calderas except that there were two magma chambers. This accounts for the oblong shape of the caldera.

The caldera is a fairly featureless plateau ringed in low hills in the center of Yellowstone park. Unlike the older two calderas in the park, the rim of Yellowstone caldera can be seen in many places around the park.

- The Washburn Overlook is on the north wall of Yellowstone caldera. This is an interesting place to view the caldera in that the south half of the Washburn volcano is down-dropped within the caldera. The caldera rim can be followed from the Washburn Range, across the Grand Canyon, to the ridge with a prominent crescentic grassy area, and beyond to the ridge on the far side of Broad Creek.

- South of Dunraven Pass there are places to stop off the road to get a good view of the caldera. This is also on the north rim of the caldera, but it gives a slightly different view than the Washburn overlook.

- Lewis Falls is on the south caldera rim. Here you can see rhyolite flows with breccia near the top.

- Lake Butte Viewpoint is a stop on the east rim of the caldera that allows for a nice 30 mile view west across the caldera.

- The road between Norris and Canyon crosses the caldera rim at the bottom of a hill just across the Gibbon River and east of the exit of the one-way Virginia Cascades drive. The caldera wall is buried here under rhyolite flows.

Post-Caldera Lava

After the formation of the caldera, there were many rhyolitic and basaltic flows that filled in the caldera and extended beyond the caldera. The flows are listed below.

Table 1: Post-Caldera Flows

Volcanic Unit		Age (Ma)
Plateau Rhyolite	Central Plateau Member (forms Pitchstone, Madison, and Solfatara plateaus	0.07-0.2
	Mallard Lake Member	0.15
	Shoshone Lake Tuff	0.18
	Obsidian Creek Member	0.09-0.32
	Roaring Mountain Member (makes Obsidian Cliff)	0.08-0.4
	Upper Basin Member	0.28-0.6
	Osprey Basalt	0.2
	Madison River Basalt	0.1-0.6
-	Swan Lake Flat Basalt (flow at Sheepeater Cliff)	0.2-0.6
	Falls River Basalt	0.2-0.6

These flows can be seen at many places around the park. There are a few nice examples.

- Obsidian Cliff, 8 miles north of Norris, is a rhyolitic unit that is 180,000 years old.

- Gibbon Canyon, as mentioned above, has an east wall made of plateau rhyolites that are 87,000 years old.

- East of Virginia Cascades, where the caldera rim is buried 0.5 miles east of Virginia Cascades, a rhyolitic flow is exposed. It is K-Ar dated at 100,000 years old.

- Firehole Falls/Madison Canyon, south of Madison Junction, exposes giant rhyolite flows. In places such as Madison Canyon, the lava ponded to thicknesses of 500-1000 feet and is topped by breccia. This breccia was formed as the top of the flow cooled and cracked as the flow continued to move.

- Pitchstone Plateau is the youngest flow from the caldera at 70,000-80,000 years old. This flow covers over 100 square miles south west of the caldera and still shows pressure ridges caused by wrinkling of cooling lava at the surface of the flow while the flow was still moving.

Resurgence
The Yellowstone caldera is not geologically dead. It moves up and down in the center (close to Fishing Bridge and Le Hardys Rapids). This is probably caused by the movement of magma underneath the surface, which may be a shallow as 3 kilometers down in this area of the park.

The first time a level line across the Yellowstone caldera was run was in 1923. The level line was not run again until 1959, after the magnitude 7.5 Hegben Lake earthquake. Scientists were a bit surprised to find that the center of the eastern magma chamber of the caldera was displaced upward in relation to the 1923 level line. Since then, many level lines have been run and the displacements carefully studied.

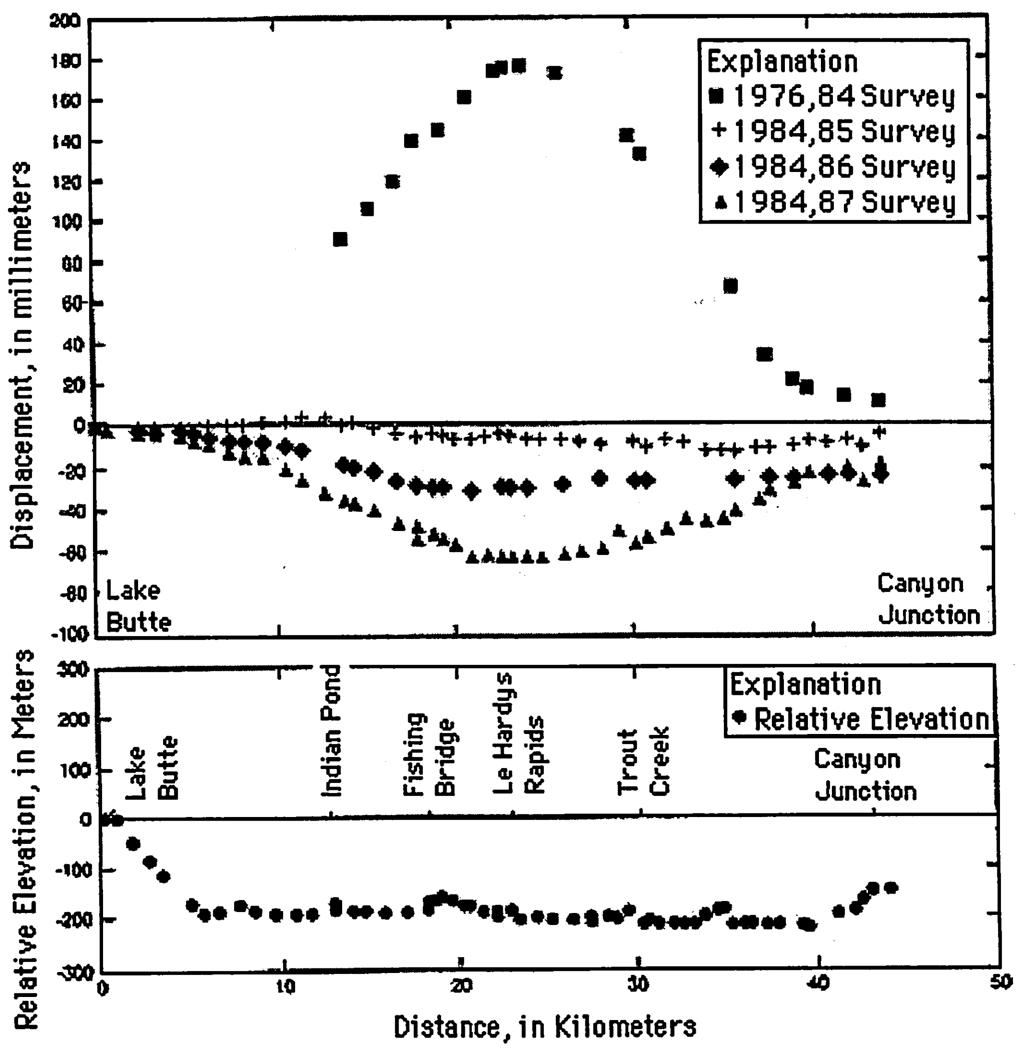


Figure 5: The top graph shows the vertical displacement and the bottom graph shows the topographic profiles along eastern leveling line from Lake Butte to Canyon Junction. Elephant Back Fault Zone intersects leveling line at Le Hardys Rapids. (Fournier et al 1994)

The most notable observation made is that the center of the caldera was going up from 1923 until about 1984, but from 1985 until present the center was going down. It is not known when the uplift started. Between 1976 and 1984, the rate of uplift was about 19.5 ± 1 mm/yr. Between 1985 and 1994, the rate of subsidence was about 35 ± 7 mm/yr.

This cycle of uplift and subsidence, while not well understood, has happened in Yellowstone before. Studies of raised and submerged shorelines and terraces show that there has been episodic uplift interspersed with local deflation throughout the Holocene. In the late Holocene, uplift at Le Hardys Rapids caused the Yellowstone River to backflood and become an extension of the Yellowstone Lake. Preliminary results of a study by K.L. Pierce (USGS) on the timing of uplift/subsidence cycles indicate that uplift /subsidence events in the past generally have been of longer duration and higher amplitude than those of this century.

Even though the caldera is in the subsidence portion of its cycle, the center is still raised above the rest of the caldera floor. In fact, the whole eastern side of the park is uplifted. Perhaps this will be the site of the next large caldera in Yellowstone park.

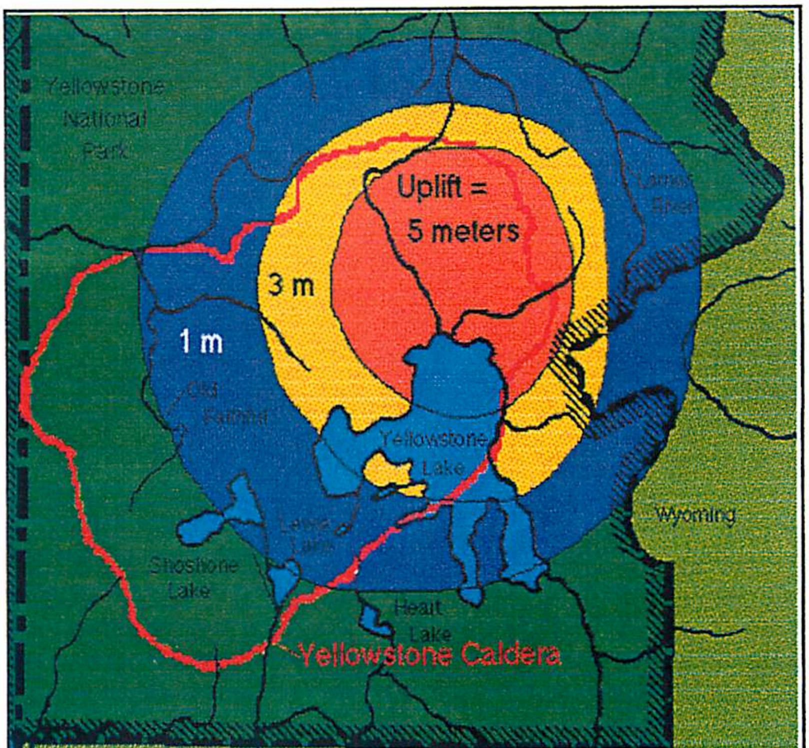
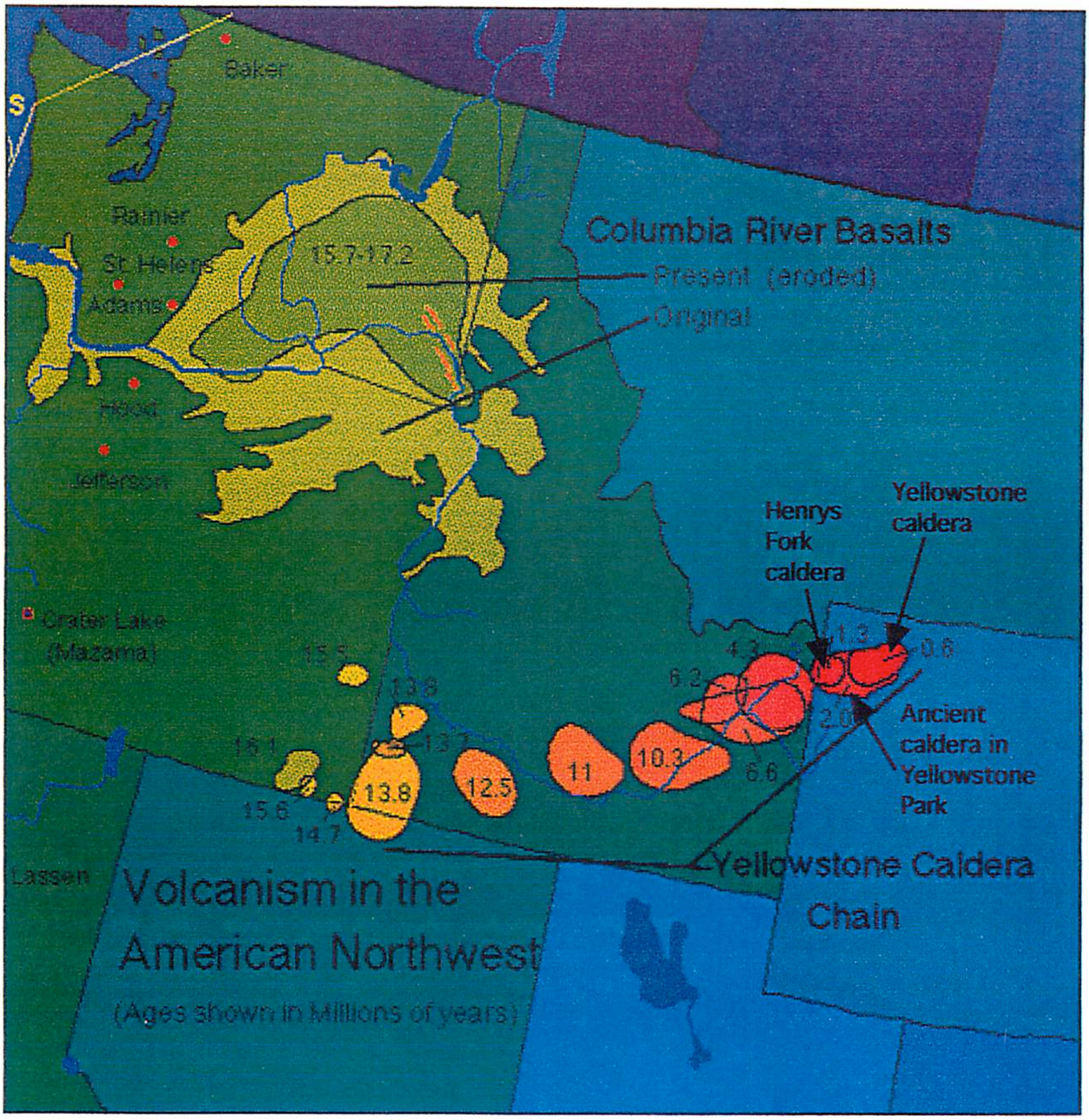


FIGURE 6: Uplift of the eastern portion of Yellowstone. (Exploring the Environment 1997)

The Planetary Connection

Calderas have been identified on Mars, Venus, and Io, in addition to Earth. This allows scientists to compare what is known about volcanism and calderas here on Earth to other places in the solar system. For example, the existence of shield volcanoes and calderas on Mars indicates that hot spot volcanism and the associated caldera collapse may be basic processes in planetary geology. The size and shape of the calderas on other planetary bodies also gives scientists a way to look below the surface at the size, shape, and depth of the magma chambers.

Appendix A
The Yellowstone Caldera Chain

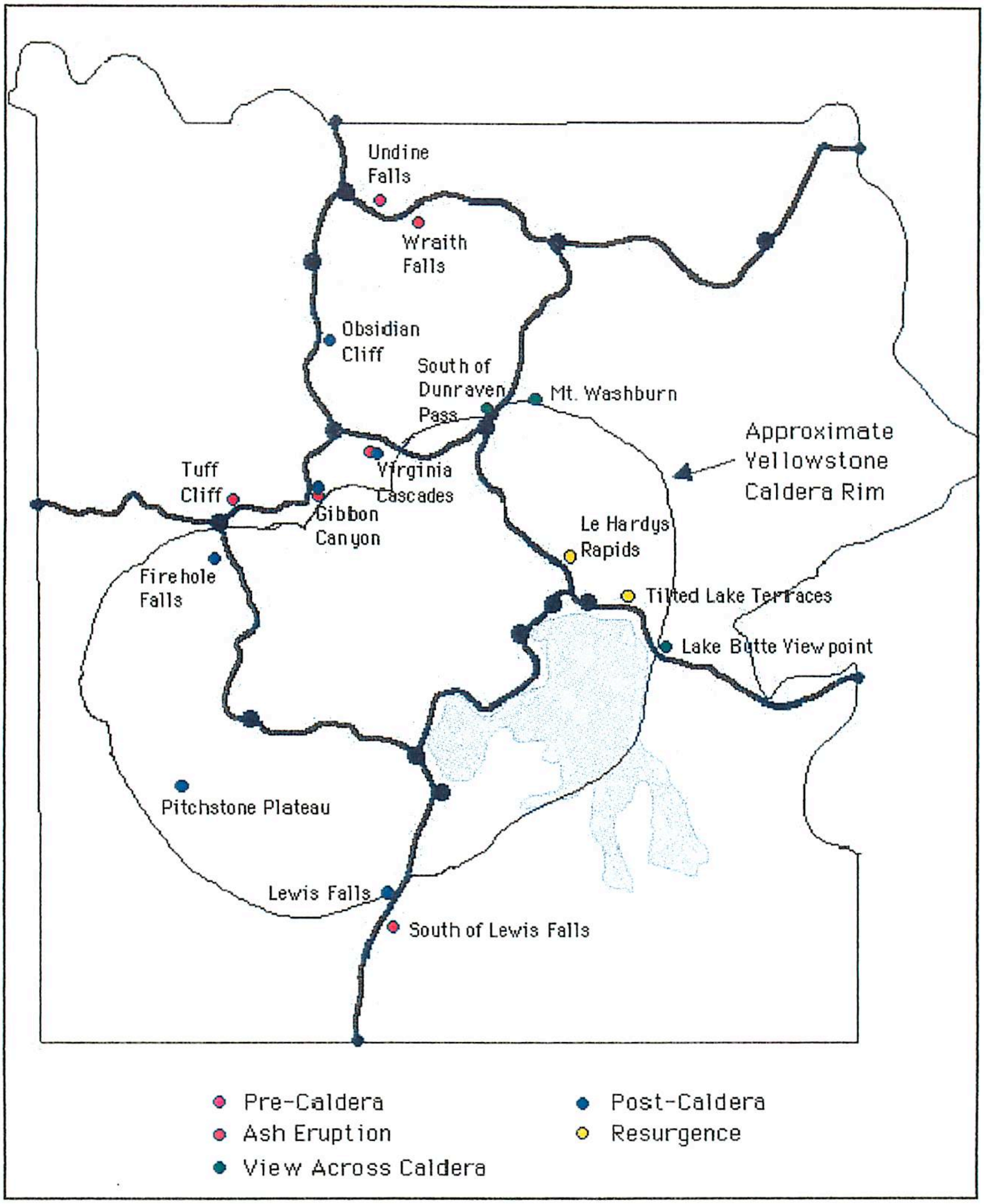


Appendix B
Volcanic Units in Yellowstone National Park

Cycle	Volcanic Unit	Age (millions of years)
Third Volcanic Cycle	Plateau Rhyolite	
	Central Plateau Member	0.07-0.2
	Mallard Lake Member	0.15
	Shoshone Lake Tuff	0.18
	Obsidian Creek Member *	0.09-0.32
	Roaring Mountain Member *	0.08-0.4
	Upper Basin Member	0.28-0.6
	Osprey Basalt	0.2
	Madison River Basalt	0.1-0.6
	Swan Lake Flat Basalt	0.2-0.6
	Falls River Basalt	0.2-0.6
	Lava Creek Tuff	**0.6**
	Undine Falls Basalt	0.7
	Mount Jackson Rhyolite	0.8
Second Volcanic Cycle	Island Park Rhyolite	1.3
	Mesa Falls Tuff	**1.3**
	Basalts of Warm River	0.6-1.2
First Volcanic Cycle	Lewis Canyon Rhyolite	0.9
	Basalt of the Narrows	1.5
	Huckleberry Ridge Tuff	**2.0**
	Junction Butte Basalt	2.2

Boldface welded-ash tuff units punctuate the explosive eruption immediately preceding caldera formation. Asterisks indicate flows that are outside the caldera rim. (Fritz 1985)

Appendix C
A Map of Yellowstone Park and Places of Interest



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THE MADISON CANYON ROCKSLIDE: DEATH AND DESTRUCTION

COURTESY OF CYNTHIA PHILLIPS

MADISON SLIDE AND EARTHQUAKE LAKE, AUGUST 21, 1959

August 17th, 1959. At the height of the summer camping season, vacationers were camped all along the Madison River in Montana, near Yellowstone National Park. The Rock Creek campground, a popular spot, was completely full, and late arrivals were turned away, some to find camping spots further down the river. All was quiet.

Suddenly, at 11:37 PM, the world of these campers was shaken. Literally. A magnitude 7.1 earthquake, centered 17 miles to the east, struck the area. The quake was felt for hundreds of miles, and every brick or stone structure within 100 miles suffered structural damage. The whole area of the Madison river canyon dropped 7-8 feet during the first minute of the quake, and this and the seismic waves triggered a massive landslide which, when the dust settled the next morning, had killed 26 people.

One family camping in the Rock Creek campground were Mr. and Mrs. Bennett, from Idaho, vacationing with their 4 kids. The parents were sleeping in their trailer, with the kids sleeping outside. Suddenly, they heard a loud noise, and the parents rushed out to check on their kids. A tremendous blast of air struck them, and Mrs. Bennett watched with horror as her husband managed to grab a tree only to be lifted off his feet by the air blast and strung out "like a flag" before being blown away. She watched as their car tumbled end over end, and then she lost consciousness. Only Mrs. Bennett and one of her sons survived.

Another family in the campground heard a tremendous grinding noise, and saw water moving upstream in the river. As the water flooded their campsite, they were able to make their way to dry land. Dawn revealed the edge of the Madison slide only 100 yards from their former campsite.

The house trailer of an elderly couple was carried 200 feet upstream in the wave created by the Slide. The couple managed to climb onto the roof of their trailer, and then into a nearby tree as the water rose over the trailer. The night wore on, with the rising water levels forcing them to keep climbing higher and higher. They were finally rescued at dawn after 5 hours in the trees.

These tragedies serve to put a human face on the massive destructive force of the Madison Slide, in which more than 37 million cubic yards of bedrock and colluvium slid into the canyon of the Madison river below Hebgen Lake. The slide owed its size and destructiveness to localized features of the topography and the bedrock structure in the wall of the canyon. The slide buried a mile of the river and a highway along it to depths of 100 to 200 feet. Water ponded by the slide formed a lake which in 3 weeks became 200 feet deep, and extended upstream almost 6 miles to a dam. The slide spread upriver to the edge of the Rock Creek campground, filled with vacationers, most of whom were hurt. The slide also buried people who had stopped for the night downstream of the campground, killing 26 people in all.

The slide occurred 17 miles west of the earthquake epicenter, and 6 miles west of the area of maximum surface deformation due to the quake. The Madison Range, through which the Madison River cuts, is in a region of Precambrian crystalline rocks, and consists mostly of gneiss, schist, quartzite, and dolomite. The slide was caused by local structural and geomorphic conditions which produced a dynamically unstable slope ready to be set in motion by flood or earthquake. Before the slide, the canyon had steep walls 1000 to 1500 feet high. A large layer of dolomite formed a wedge approximately 500 feet wide and 1 mile long at river level, and tapered upward and eastward between faults and the erosion surface. This body of strong rock served as a structural buttress supporting the lower part of the canyon wall. During the slide, a section of the southern canyon wall 2200 feet long, and 1300 feet high, slid northward into the canyon, spreading over an area of 130 acres on the canyon floor and adjacent slopes. The slide scar reached the crest of the ridge on the south side of the canyon, and in some places cut as much as 200 feet vertically down the backslope. The upper limit of the slide was determined by a weak zone of sheared and altered schist, and the top of the scar followed a shear zone in some areas and the ridge crest in others. The lateral boundaries of the slide were determined by topographic and dynamic features: the western boundary followed a steep ravine between two dolomite spurs, while the eastern boundary was controlled by the direction of motion of the mass as a whole.

The slide pushed a wave of muddy water carrying trees and rocks upstream ahead of the slide mass, which reached a maximum height of 100 feet above the river on the northern wall of the canyon. This wave engulfed the Rock Creek campground, injuring the people camped there and destroying much property. A similar wave downstream carried logs up to 3/4 mile , and battered and swept two cars for 100 yards beyond the edge of the slide. Upstream of the slide, the blocked river ponded and formed Earthquake Lake. The water level rose fast, due to the small area and surges in Hebgen lake across the dam (where the water oscillated due to the quake). By 6:30 AM, the water had risen 20 feet, submerging all the remaining vehicles in the Rock Creek campground. Worried about a flood when the water finally crested over the slide mass blocking the river, the US Army Corps of Engineers constructed a spillway, burrowing through the slide mass to make a channel to control the water flow. They constructed a trough 200 feet wide and 1/2 mile long, and on September 10th, 24 days after the quake, water began flowing downstream again. By this time, Earthquake Lake had grown to 10 km long and 60 m deep behind the slide.

The resulting slide debris covered an area of 130 acres in the bottom of the canyon to an average depth of 150 feet and a maximum depth of 220 feet in the river channel. Most of the slide debris crossed the river, and the highest point was reached by the light-colored dolomite debris at the toe of the slide, which ran up the opposite side of the canyon and reached to a height of 430 feet above the river. Calculations estimate that the center of mass of the slide traveled 1600 feet on a 30° slope, and would have required a maximum velocity of about 100 mph, and taken 20 seconds to come down. The western end of the slide broke out well above the valley floor, agreeing with the violent air blast reported by witnesses which would have resulted from the expulsion of air trapped below the descending debris. The top few feet of the slide mass contained mostly larger fragments, and below that they are mixed with finer fragments. The slide debris is mostly gneiss, but bands of schist, lime-silicate gneiss and dolomite parallel the toe of the slide and preserve the order in which these rocks formerly existed on the ridge. The light-colored dolomite band traveled the farthest. Most of the blocky pieces of debris are 1-2 feet long, but a few are larger, with the largest block being a house-sized piece 30 feet long.

The slide is thought to have been caused primarily by slope instability and the energy input from the earthquake. The slide seems not to have been affected by climate or flooding, as is common for slides of this magnitude, but was rather due to an instability produced by the geomorphic effect of the dolomite wedge in the lower part of the canyon. This dolomite buttressing allowed a slope angle of 40° to develop, which is steeper than is consistent with the strength and resistance to erosion of the schist and deeply weathered rock in the ridge behind it. The slope east of the slide is 25°, which is more consistent with the intrinsic strength of the materials. Thus a mass of weak rock, held in place largely by friction, was suddenly transformed into a mass which flowed into the canyon. Water saturation was not a factor in the slide, as the conditions were dry and cool, and the slide produced large clouds of dust which were visible for several miles and obscured the scene for some time after the event.

Some landslides have air trapped beneath the slide which is compressed and serves as a cushion, facilitating the travel of the slide debris. A violent airblast did occur, as reported by witnesses, but there is little evidence that the trapped air was a significant factor in the travel of the slide mass. On the western (downstream) end of the slide, debris and fish were thrown 300 m beyond the end of the slide, and two cars were found completely battered. The western part of the slide mass broke out well above river level, and trapped air under it which rushed out as the slide mass dropped to the floor of the canyon. This trapped air may have been a factor in the slide movement, but could not have been very effective, since the distance traveled by the western part of the slide is much less than that of the eastern part of the slide where no air was trapped.

Thus, the main cause of the slide seems to be the kinetic energy introduced by the slide and the regional ground subsidence of 7-8 feet. Steep slopes were maintained by friction and strength, with dolomite the strongest component of the ridge. The kinetic energy introduced by the seismic waves was sufficient to overcome the friction and strength, and produced surface flow in the upper part of the slide, and glide movement in the deeper part. NE-trending faults and foliation surfaces aided the sliding of the eastern part of the slide, and the base of the main slide was controlled by topography. Witnesses report no gap in time between the first earthquake shock and the slide, so the slide must have been triggered by the first shock and not due to pent-up strain from a series of aftershocks.

The end result of the slide was the death of 26 people (2 others died due to unrelated rockslides, so the earthquake itself had a death toll of 28). The violent displacement of the water of the Madison river by the rockslide overturned camping trailers, bowled over tents, and caused human injuries and loss of life. Barked trees and debris were found scattered high along riverbanks for 1/2 mile below the slide, and the slide mass formed a relatively impervious dam which stopped the flow of the river for weeks.

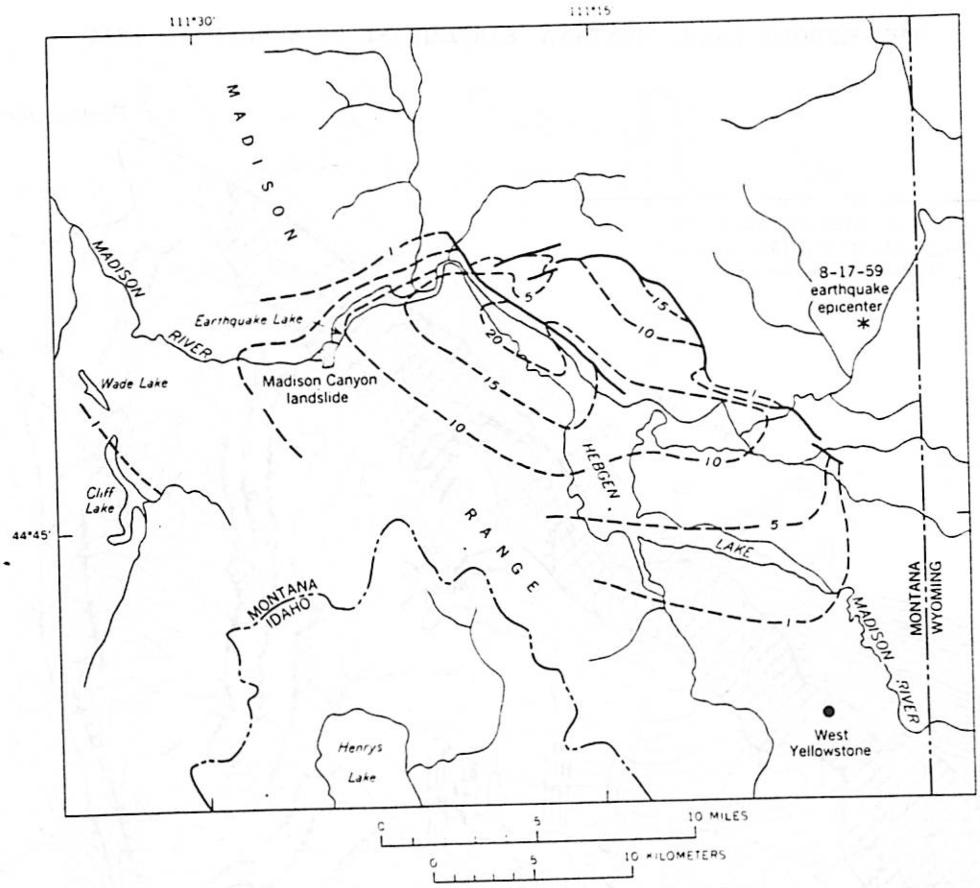

Fig. 1. Location map of the Hebgen Lake earthquake area (from *U.S. Geological Survey Professional Paper*, 435, plate 2). Isobases show ground subsidence in feet accompanying the 1959 earthquake; heavy lines are fault scarps.

Fig. 8. Battered automobile in the dry-bed of the Madison River below the Madison Canyon landslide (photograph by U.S. Forest Service).

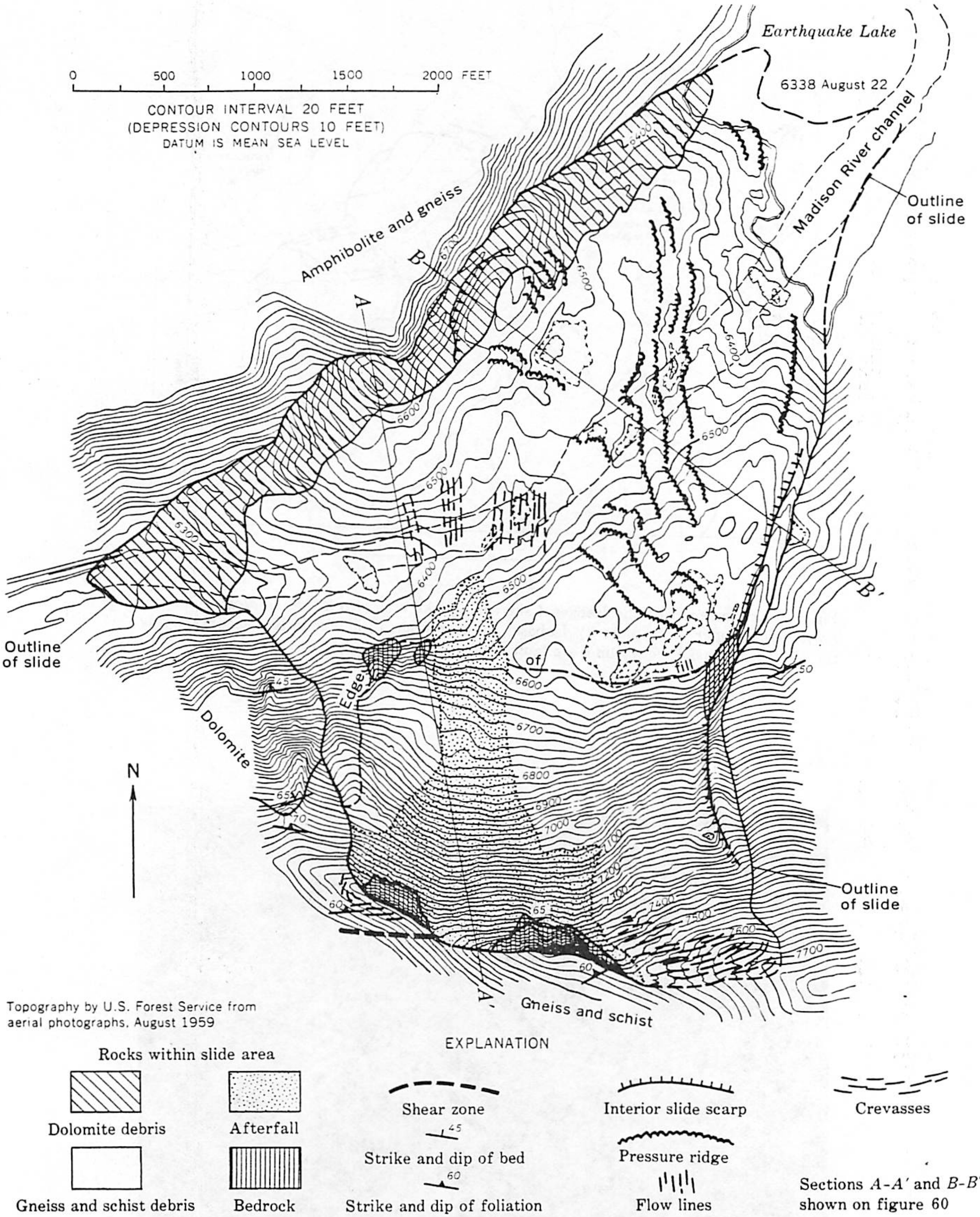

FIGURE 59.—Topographic and geologic map of the Madison Slide.

FIGURE 54.—Madison Slide, upstream view showing the west edge of the slide debris, blocked highway, and dry river bed below the slide. U.S. Forest Service photograph.

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Landslides

Josh Emery, Univ. Ariz., 1997

Landslides can occur in a number of geologic settings, from mountain ranges to glacial valleys to volcano flanks and calderas to continental shelves and mid-ocean ridges and even basin and crater walls. They can also have a wide variety of immediate causes (e.g. weathering, basement uplift, tectonic activity, volcanic activity, etc.).

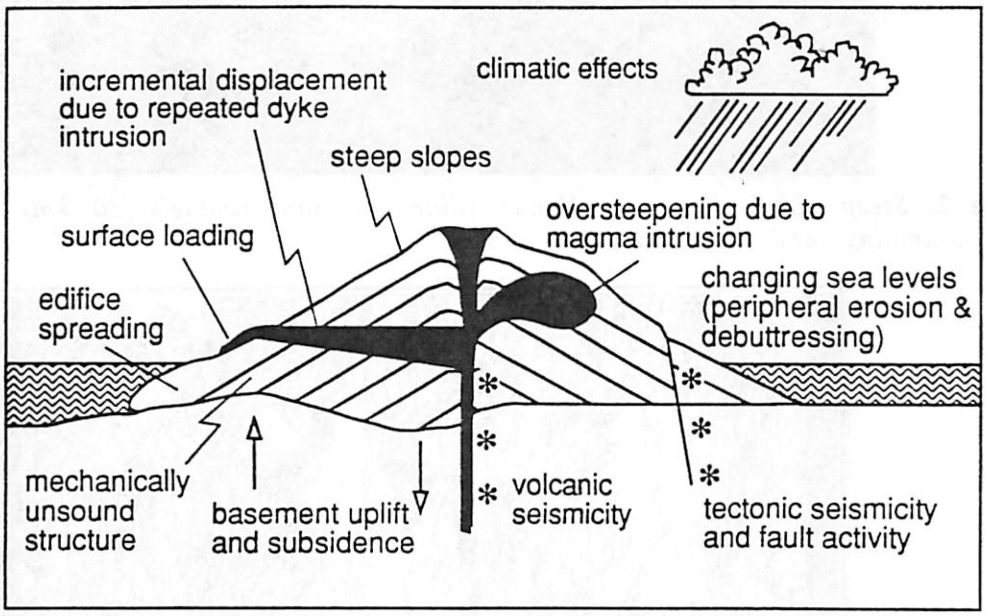


Figure 1. *Factors contributing to development of instabilities leading to landslides. While these are all shown in the context of a volcano, many of the factors would apply equally well in most other geologic settings (e.g. climate effects, changing sea levels, tectonic activity, basement uplift, etc.).*

No matter what the geologic setting or immediate trigger are, all landslides are essentially the gravity driven mass transfer of material downslope from the source to an area of deposition. However, characteristics of the specific setting necessarily affect the details of any individual event. These characteristics include such parameters as slope steepness, debris type, amount of mass being moved, and atmospheric pressure and gravity for landslides on other planets. Water can play a major role in both the triggering event (e.g. erosion leading to instability) and in the mechanics of the slide itself ("lubrication" of debris by providing conditions of high pore pressures).

Comparisons of landslides on Venus, Earth and Mars show that, in general, events on Venus have the longest run-out distances for a given drop, terrestrial run-out distances are slightly shorter, and Martian run-out distances are shorter still. The main reason for this is thought to be differences in atmospheric pressure, although differences in debris type and size may also play a role.

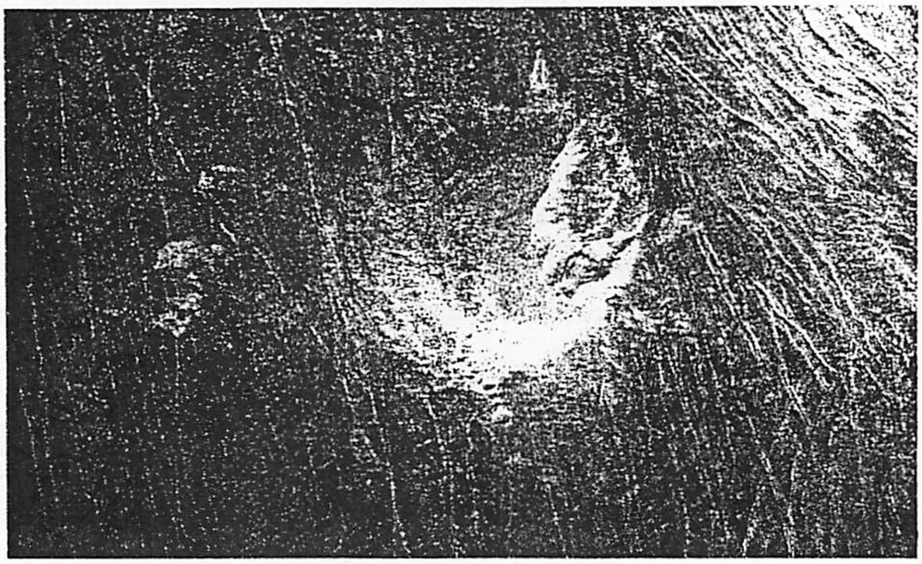


Figure 2. *Steep sided dome on Venus (diameter approximately 30 km) showing slumping and landslide.*

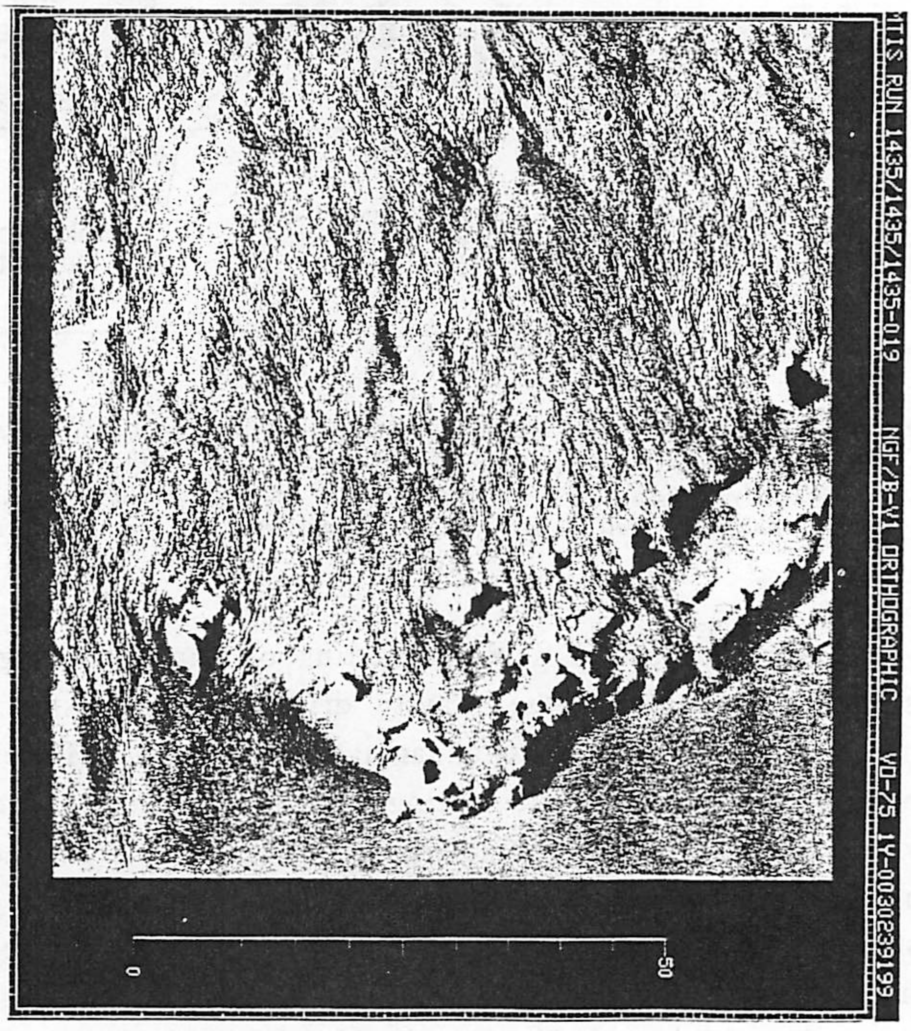
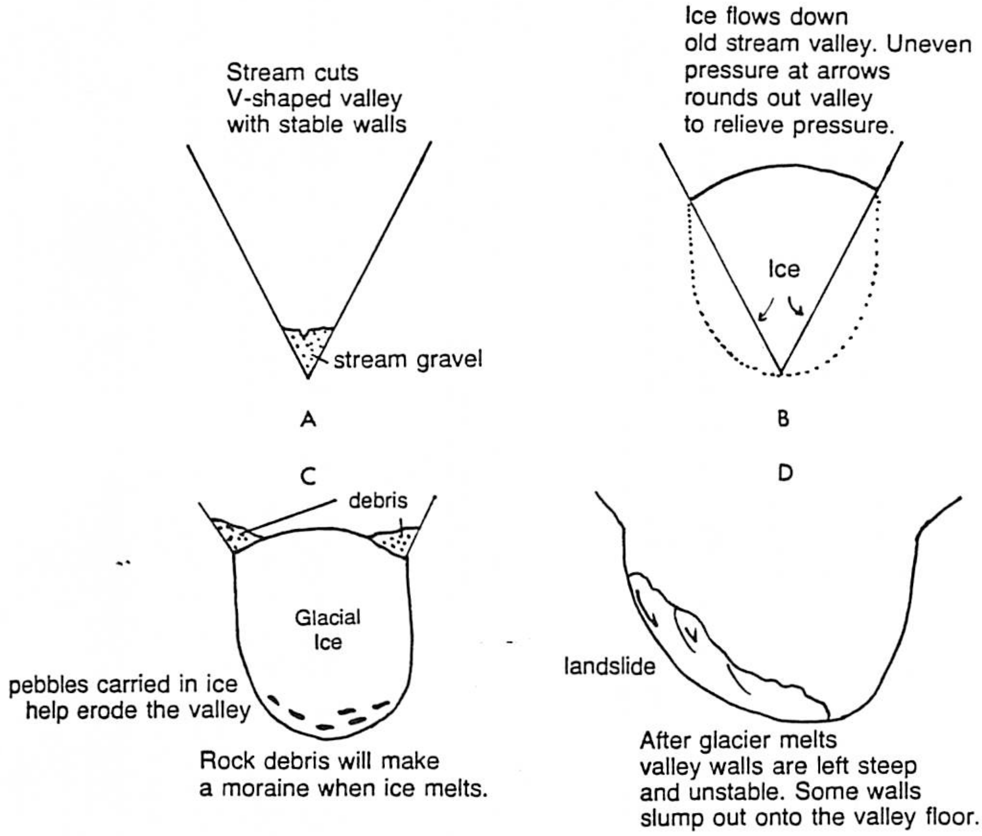


Figure 3. *Detail of flanking scarp of Olympus Mons (on Mars). Can see debris flow covering parts of scarp.*

Landslides in and around Yellowstone have been triggered by tectonic activity and climate effects, the steep slopes having been emplaced mainly by erosional processes, including glaciation. Large mudslides have been induced by the eradication parts of some forests (by fire) which are the stabilizing force on hillsides.



Sequence of events that have shaped the Lamar River Valley and many similar valleys in northern Yellowstone.

A small landslide with a scarp, hummocks and toe along the road by the Lamar River picnic area.

Fires in the Yellowstone Park

Luba Florinskaia

Between the Yellowstone National Park establishment in 1872 and the 60's of our century, the policy of the park management targeted to protect the forests from fires. In the 1960's ecologists began to study naturally occurring fires in the park and elsewhere as necessary ingredients of the ecosystems. By studying tree rings scientists were able to reconstruct fire records in the park since the end of the XVI century. It was found that the largest fires occur every 200 to 400 years. This time is necessary for the conifers to fully grow back and die to be replaced by the next generation of trees. Only after enough fuel (mostly dead trees) accumulate and the smaller trees grow creating a middle layer between the canopy and the undergrowth, can the forest support a major fire (see Fig. 2 for the ecological cycle of a forest). Fires are usually ignited by lightning.

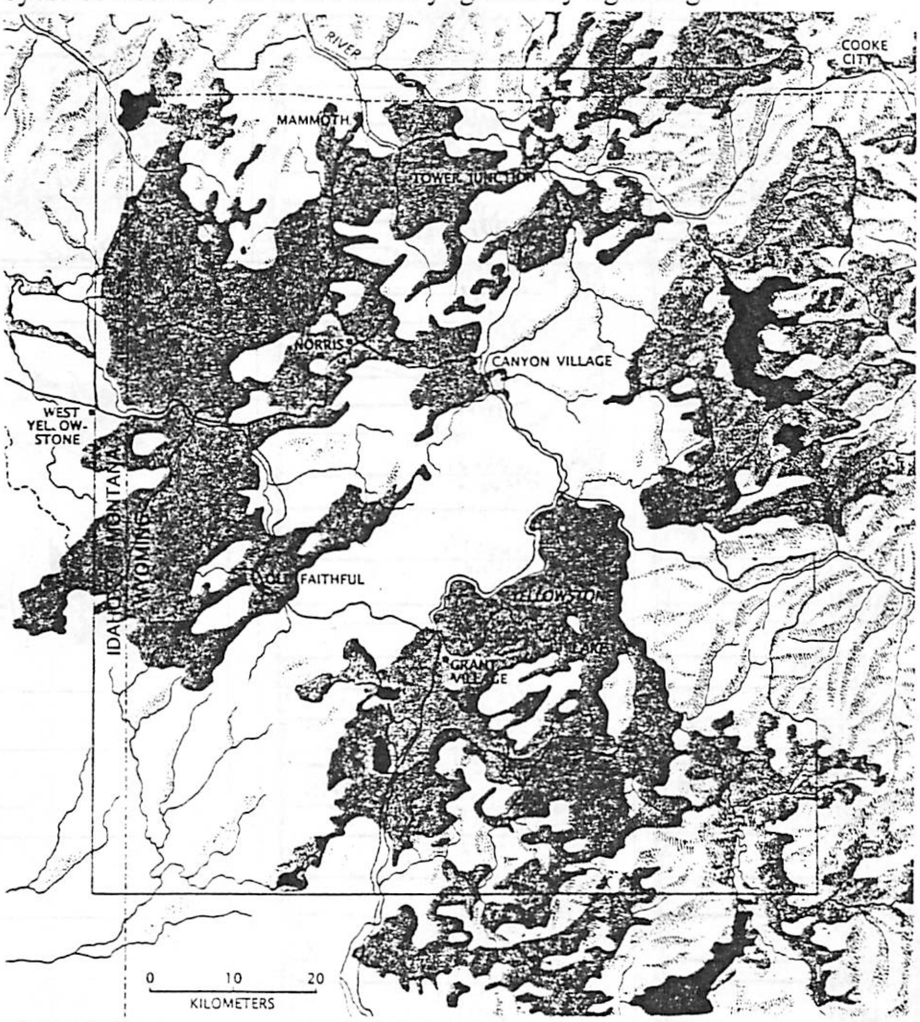
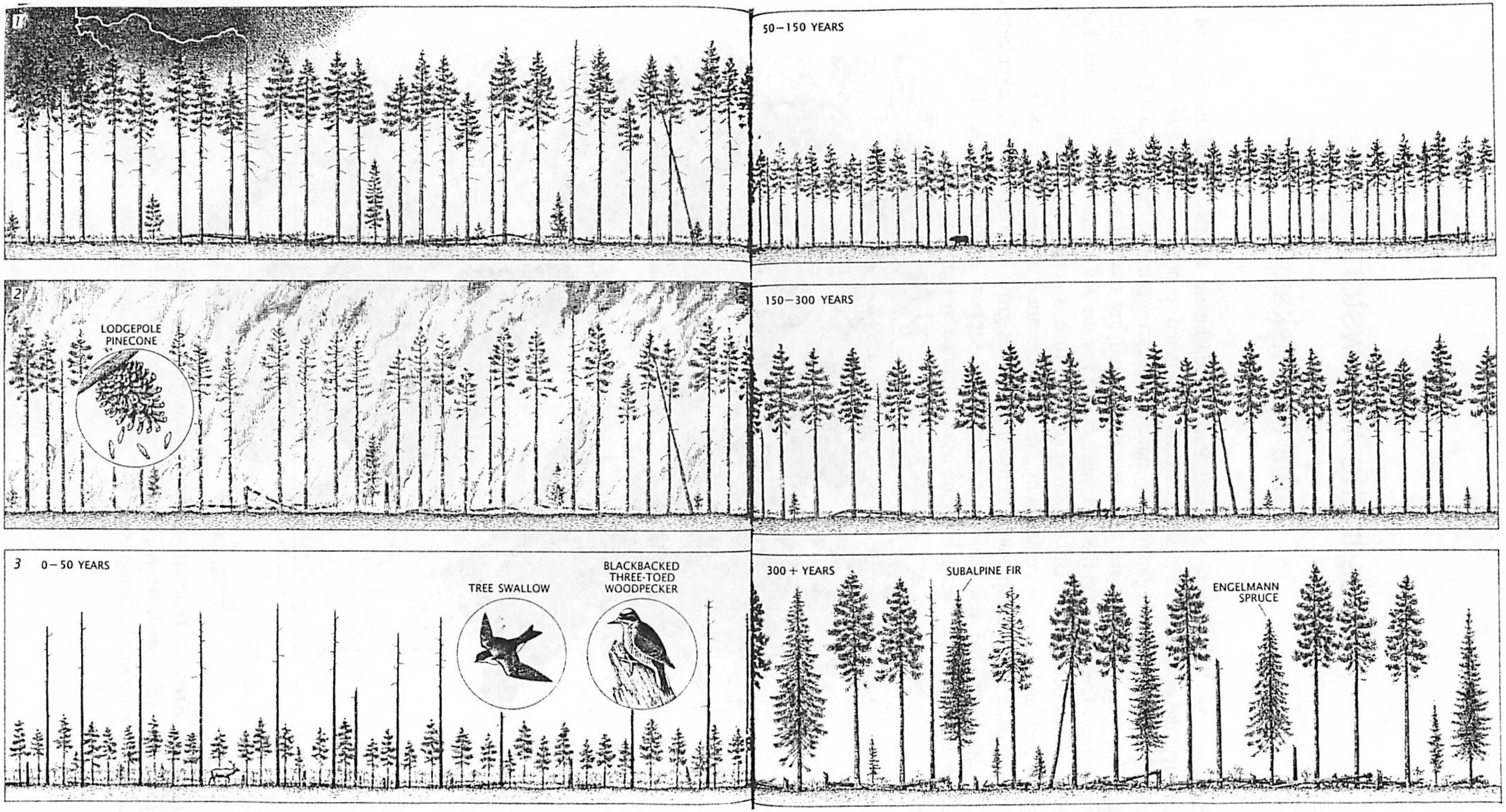


Figure 1. Areas of Yellowstone Park and surrounding areas burned by the fires of 1988. Darker shading indicate regions where the fires started in July while lighter shading show their spread by October of 1988 (from Romme and Despain, 1989*).*



ECOLOGICAL SUCCESSION can be divided into stages, each of which is represented above. Here an old-growth forest in Yellowstone, consisting of lodgepole pine, subalpine fir and Engelmann spruce, has been struck by lightning (*1*). If the ensuing fire is severe (*2*), most vegetation will be destroyed. Lodgepole pinecones protect their seeds during a fire; afterward, they open and release their seeds, which germinate at about the time the roots and seeds of many herbaceous species resprout, thus initiating the first stage of succession (*3*). During that stage the open, sunny forest supports many species, including birds, such as swallows and woodpeckers, and elk. Lodgepole saplings may grow to 15 or 20 feet. After about 50 years the forest enters the second stage of succession (*4*), which lasts for about 100 years. During this period the pines reach heights from 30 to 50 feet and form dense stands that block the sun. In the third stage (*5*), which starts after some 150 years and lasts for about a century, the lodgepole pines thin out, and second-generation trees such as the Engelmann spruce and subalpine fir appear. Increased sunlight stimulates the growth of vegetation on the forest floor. In the last stage of succession (*6*), when the forest is about 300 years old, the original trees die, and large gaps appear in the canopy. Small trees and dead branches accumulate, and the forest, which is now highly flammable, is once again vulnerable to fire.

The last such major fire occurred in Yellowstone during the summer and fall of 1988. Over 720,000 acres burned (about 33% of the total park area, see Fig. 1). Two major conditions caused the fire:

a) Forest "maturity": the last such major fire occurred in the early XVIII century, and
b) Exclusive weather conditions: the worst drought in the 112 years before the fire.

Most of the Yellowstone sits on a plateau with elevations between 7,000 and 9,000 feet. In these areas air is less humid, soil is dry and winds are stronger than in the valleys, all making fires more likely to happen. The burnt areas exhibit a highly irregular pattern. Areas with lots of young vegetation and river valleys, covered with reeds, suffered less from the fire.

The animal and bird populations suffered little from the fire. Only 350 elk and 9 bison died of smoke suffocation. Usually animals are able to escape a fire. Birds of prey flourished on small animals migrating from the burning areas. Most birds will readily nest in the burnt regions once the insect population is replenished.

In the years following the fire, plants grows in abundance since the soil is fertilized with ash and the thick canopy no longer blocks the sunlight. However, in the worst burnt areas the ground is baked making it water-repellent. Plants grow from the seeds remaining in the soil after the fire. The Yellowstone region has a dry climate and the dead tree trunks break down slowly. After the fire, much of the nutrients contained in dead trees returns to the soil, but most of the nitrogen is not retained (released into the atmosphere).

Observations show that during the years following a fire herds of grazing animals from outside of the park borders come to the park to feed on rich grass. This leads to increase in predator population. Fires also increase nutrient contents and temperature of rivers and lakes leading to proliferation of water life, including algae and fish, the latter attracting pelicans, ospreys and grizzly bears.

Conclusion: Naturally occurring forest fires are integral part of the Yellowstone ecosystem balance. However, it is still necessary to monitor their rate of occurrence and take measures to stop fires started by man.

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✎ This article was edited and translated by Vladimir Florinski ✎

The Future of Yellowstone

Eruption Prediction: How and When Will We Know? (and will Grant Village campsite explode while we are there?)

brought to you by your hostess with neuroses
Jennifer A. Grier

I. Introduction

It is obvious that the Yellowstone National park area is a highly active thermal zone. The history of the area is replete with hydrothermal and volcanic activity, including times of relative quiescence interspersed with times of great explosive eruptions. The history of the region can be read in the rocks, but what about the future? Will activity in the region fade or flare, and how can we tell? Recall that the volume of materials, and the global impact of past eruptions in Yellowstone vastly exceeded that of Mr. Pinatubo and Mr. St. Helens; will the future be as violent? And in the end, do we really want to know what the chances *are* of our campsite exploding in the middle of a fireside chat? Read on ...

II. Volcanic Activity Potential and Eruption Prediction

In order to get a handle on this, you need to check lots of stuff, but a good place to start is age dating, seismicity, geoid, topography and heat flow.

<u>Age Dating and the Hot Spot Track - Rocks Old to Young</u>

Across the Snake River Plain and into Yellowstone is a long series of volcanic rocks and related calderas. Dating of the rocks shows that the track begins > 16 Ma ago on the Oregon border, and continues with rocks of progressively younger age through Idaho and into NW Wyoming. This corresponds to a silicic volcanic age progression rate of about 4 +/- 1 cm/yr. Although the plate moves only 2 cm/yr, the crust is extending in a Basin and Range fashion at the same time, and thus the 4 cm/yr average. The assumption is that a hot spot of relative fixed position is punching its way through the crust, and as the crust extends and moves, so does the silicic volcanism that the hot spot generates. The movement is not uniform. There are at least two separate regimes: 20-10 Ma at 3.1 cm/yr (267 deg), and 9-0 Ma with a rate of 2.9 Ma (234 deg).

Heat Flow - It's Hot!

The background heat flow from the NA continent is about 40 to 60 mWm-2. This is in contrast to the average from he Yellowstone Region of ~2000 mWm-2. The highest flux is found near Mallard Lake Dome, which measures a huge ~58,600 mWm-2. The ~2000 mWm-2 is comparable to the entire Cascade Range.

Seismicity - Consistent Earthquake Activity

Using seismic information, one can gain insight both into the movement of the Yellowstone hotspot for the last 16 Ma, as well as into the detailed structure of the Yellowstone Park area itself. Complementing the track of the hotspot across Idaho is a parabolic shaped wave of seismotectonic domains. In contrast, the Snake River Plain, which the parabola surrounds, is relatively quiet. While the mechanism which produces this pattern is not understood, the connection between the seismicity and the hot spot seems apparent. On a local scale, seismicity in the Yellowstone region is very high. Even the first explorers noted the seemingly constant shaking of the ground and frequent landslides. From 1973-1990 intense swarms of shallow earthquakes and occasional larger events characterized the activity in the region. Seismicity and new hydrothermal activity are often linked, especially with earthquake swarms. The regional tectonic stress field, closely related to the movement of the hot spot and crustal extension, controls the local seismic patterns.

Geoid - Anomalously High

Recall that the geoid represents the degree of long-wavelength isostatic compensation, determined by gravity field measurements. Differences in density and topographic relief etc., combine to create compensation features on this surface. Now, the most significant anomaly on the geoid equipotential surface on the continent of NA is centered on Yellowstone. This signature is produced by a combination of the 600 m excess height of the Yellowstone plateau, and a low-density area in the upper mantle (hot spot). The size of this anomaly is similar to that of those found on the ocean floor.

Topography - Changes Quickly

Changes in local topography in the Yellowstone region, and specifically related to the Yellowstone Caldera allow for estimates to be made of the depth and amount of thermal fluids. From 1923-1984 the was a period of uplift in the caldera (connected with the resurgent domes) totaling about 1m, which was then followed by a period of subsidence across the entirety of the caldera of about 25 cm from 1985 to 1991. This indicates that there are shallow magmatic/hydrothermal fluids. The timing of the subsidence/uplift indicates that the reservoir is probably connected underground between at least the two resurgent domes, and possibly throughout the full 75 km extent of the caldera.

III. Future Predictions

There seems little evidence that magmatic and other thermal activity will cease anytime soon, thus volcanic eruptions are quite likely in the future. The nature and extent of the crustal deformation in the Yellowstone region, and the continuous volcanic activity reflects a very strong, and long lived source of heat for powering this activity.

As indicated, the volcanic activity appears to go in cycles, and it is not entirely clear where we are in the present cycle. It has been speculated that we may be in the end of the third or beginning of a new forth cycle.

A reawakening of intense volcanic activity would probably be preceded by increased earthquake activity. The present level of seismicity in the region is not sufficient to indicate imminent activity. Large Earthquakes, greater than 7.5, would probably occur on the edges of the Yellowstone plateau, with large number of smaller, ~6.5 earthquakes around the edge and within the caldera.

Also to watch out for would be any change in the evolution of the fumeroles, geysers, and hotsprings. These formations are powered by the circulation of hot water underground, and volcanic activity can alter or extinguish these by causing underground changes in water circulation patterns. Uplift, subsidence, fault movement during earthquakes, rapid emplacement or withdrawal of magma etc. can all alter the hydrothermal formations within the region.

IV. The Final Call

Well, it looks as though our campsite will not explode while we are there, but it also appears that another large explosion related to another series of silicic volcanism is highly likely on short geologic timescales. Since the underground fluid system is connected, the caldera may blow from almost anywhere, but most likely a resurgent dome will burst. Given the progress of the Yellowstone hot spot to the NE, the Sour Creek dome may be next, but the high heat flow from the Mallard Lake come region may indicate that this is a more active area.

References: Several articles contained in: Steidtmann, J.R., and Roberts, S.M., edts, Geology of Wyoming: GSW Memoir #5, p 694-754, 1993. Figures from: Smith, R.B. and L.W. Braile, Topographic signature, space-time evolution, and physical properties of the Yellowstone-Snake River Plain volcanic system: the Yellowstone Hotspot, in Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., edts, Geology of Wyoming: GSW Memoir #5, p 694-754, 1993. Fournier, Christiansen, Hutchinson, and Pierce, 1994. USGS Bulletine 2099, A field trip guide to Yellowstone National Park, Wyoming, Montana and Idaho. Volcanic Hydrothermal, and glacial activity in the region.

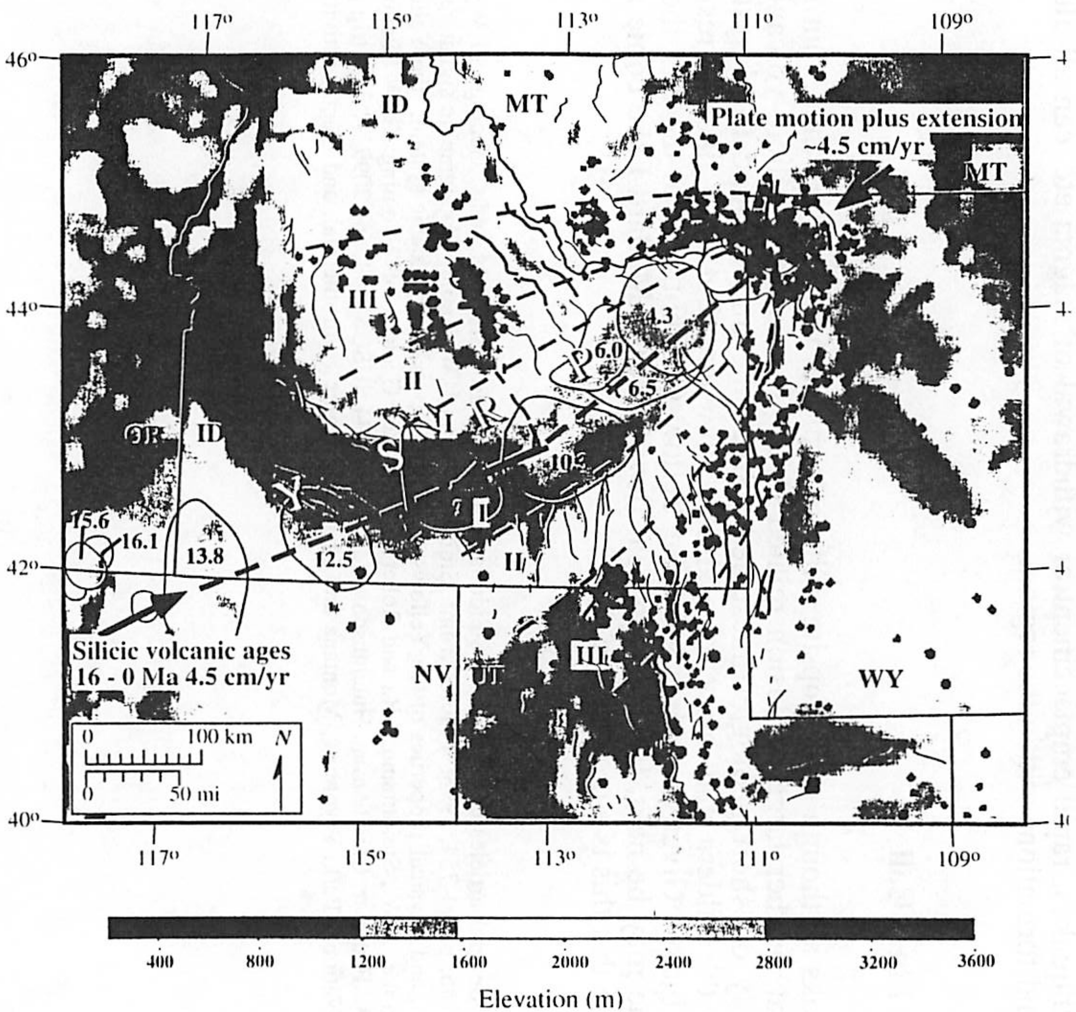


Figure 4. Topographic and seismicity signature of the Yellowstone hotspot, showing the "bow-wave" or parabolic-shap seismotectonic domains (defined in text) I, II and III. Earthquake epicenters are shown as black filled circles and are scaled in si to magnitude; 2.5 ≤ M ≤ 7.5, for the period, ~1900 to 1985. The earthquake data are from earthquake compilations of th Intermountain region by the University of Utah (Eddington and others, 1987; Smith and Arabasz, 1991) and Engdahl and Rineha (1988).

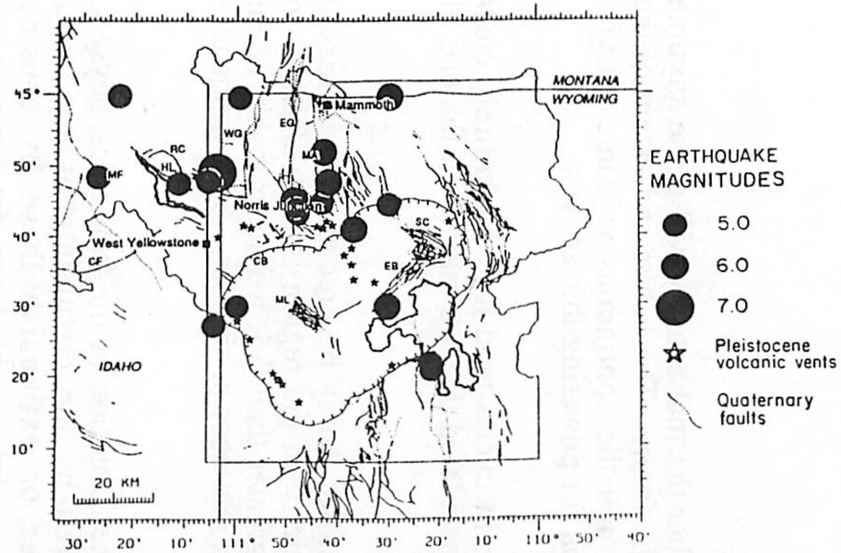


Figure 13. Map of Quaternary faults, Pleistocene volcanic vents, and larger, historic earthquakes (M > 5.5) of the Yellowstone Plateau. Volcanic vents are from U. S. Geological Survey 15-minute geologic quadrangle maps. Faults were digitized from the maps of Christiansen (1993). Fault zones are: RC = Red Canyon, HL = Hebgen Lake, WG = West Gallatin, EG = East Gallatin, CB = caldera boundary, EB = Elephant Back, and MA = Mammoth corridor. ML = Mallard Lake dome and SC = Sour Creek dome.

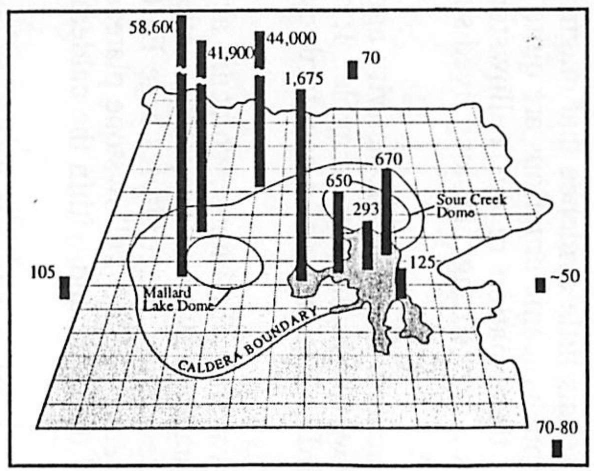
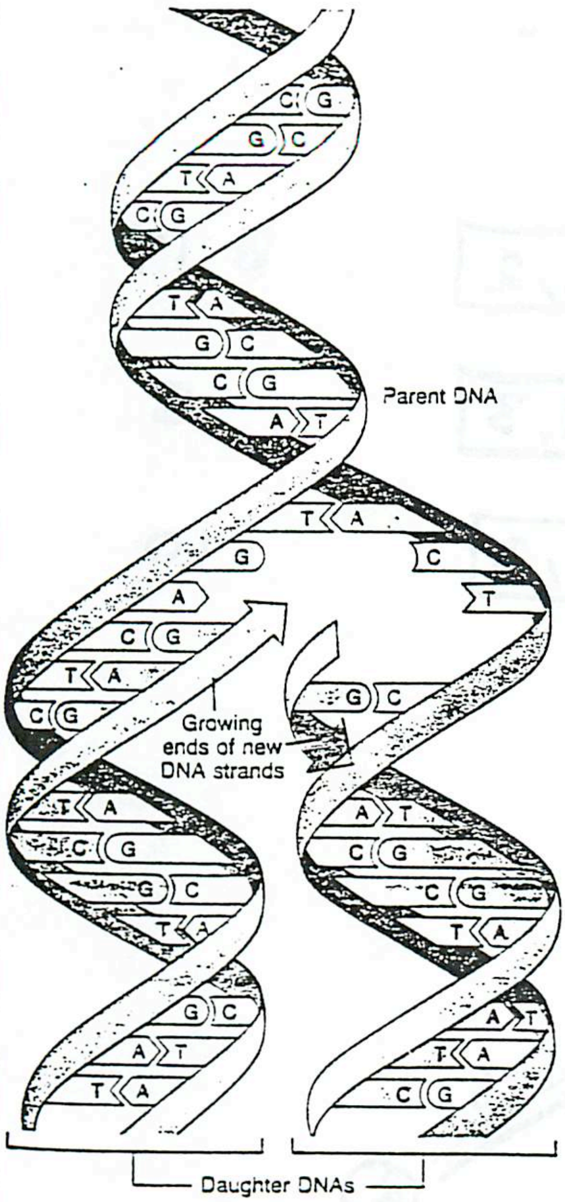
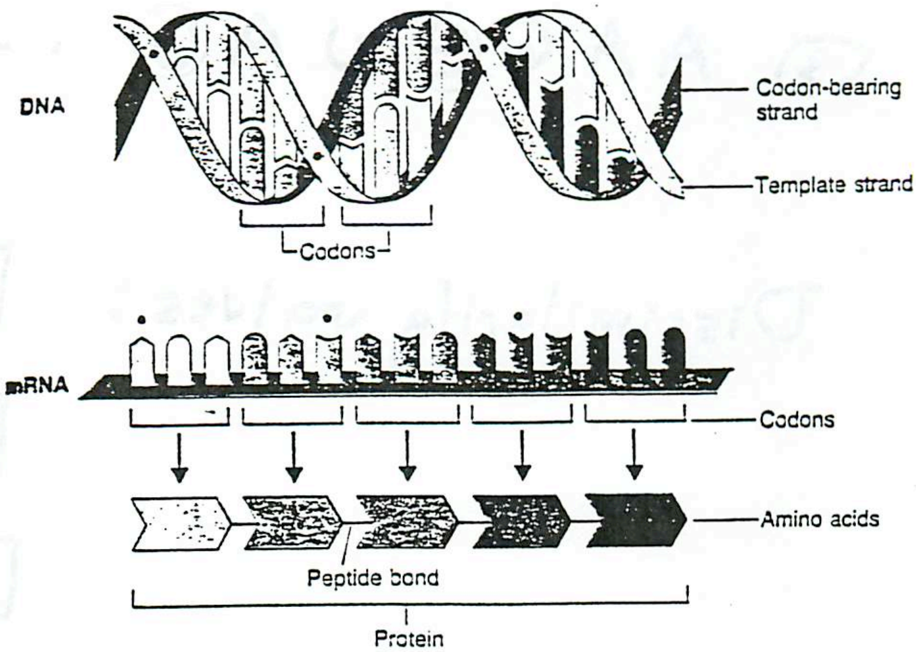


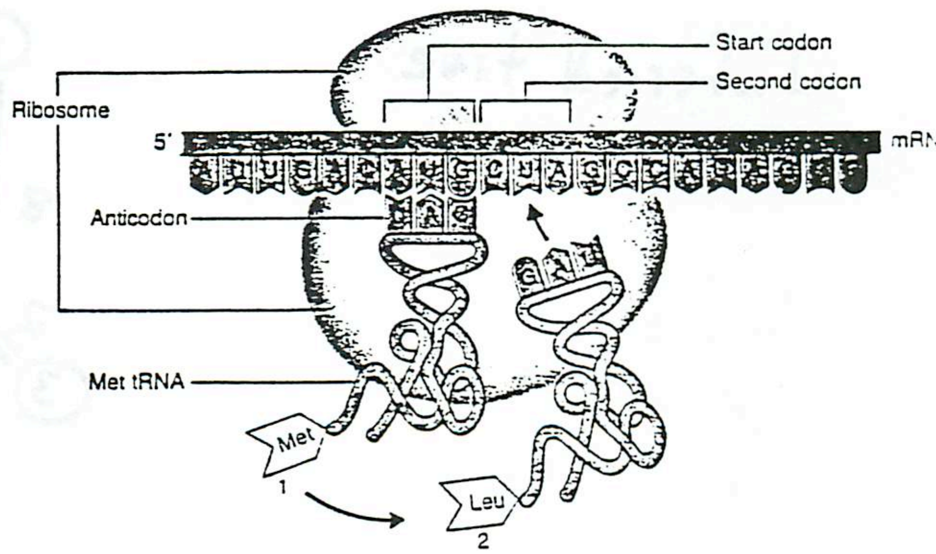
Figure 16. Heat-flow distribution of the Yellowstone Plateau (in units of mWm^{-2}). Heat-flow values in Yellowstone Lake were determined by thermal probe measurements and are considered the most reliable indicators of the conductive heat flux of the Yellowstone caldera (Morgan and others, 1977). Heat-flow values for the western caldera were estimated from geochemical determinations by Fournier (1989) and mainly reflect the convective component of heat flow. Heat-flow values of the surrounding region are from Blackwell (1989) and Heasler and Hinckley (1985).

RNA, Molecular Phylogenies, Thermophiles, and the Deep Biosphere

Christopher Chyba







Sequences:

① A A G C U A G . . .

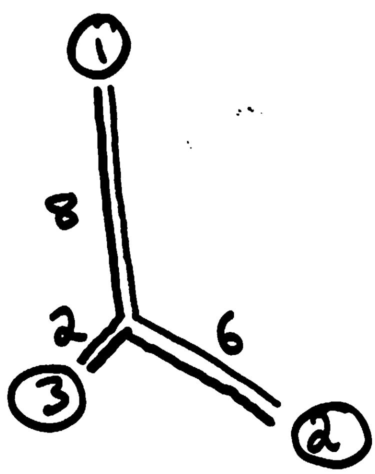
② A G G G U A U . . .

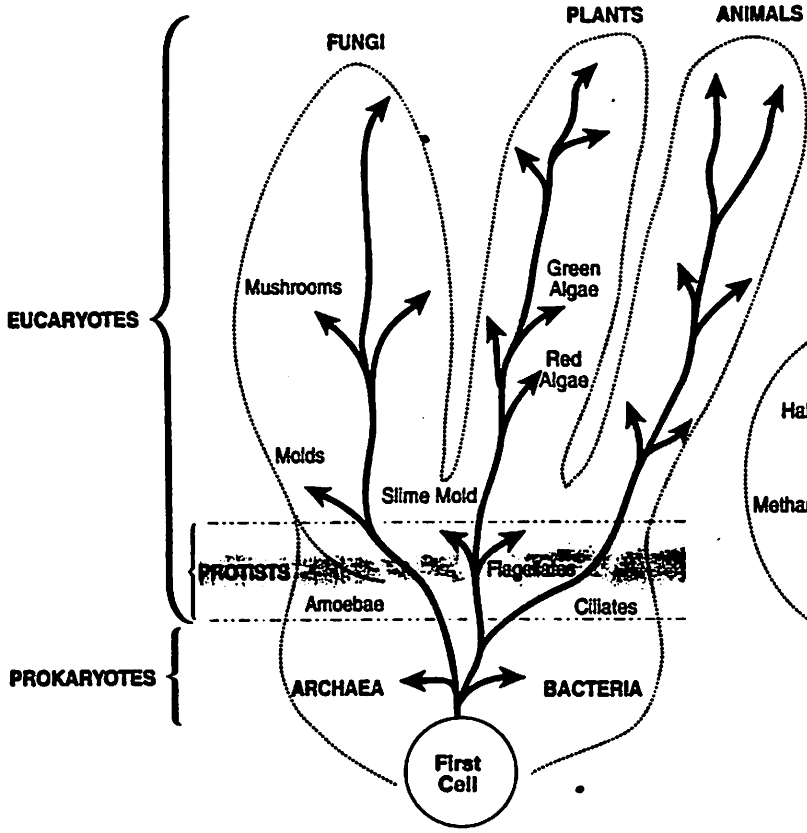
③ A A G G U A U . . .

Dissimilarity values:

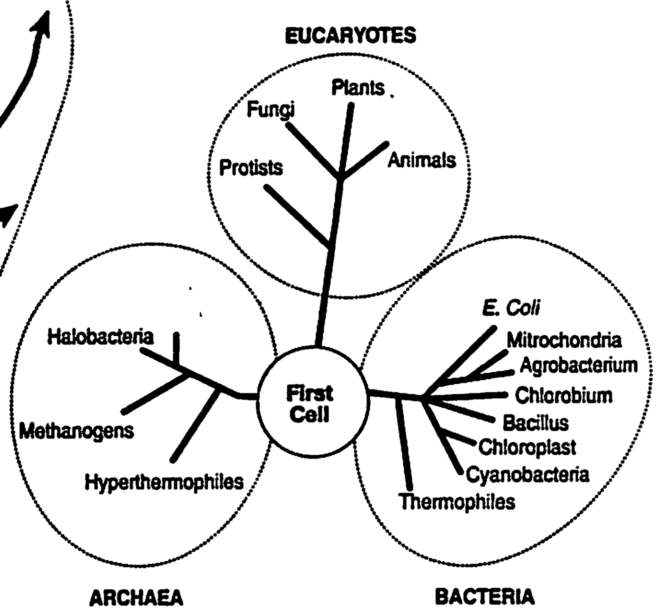
1,2	14
2,3	8
1,3	10

Inferred tree:





"CLASSICAL" PHYLOGENY



MOLECULAR PHYLOGENY

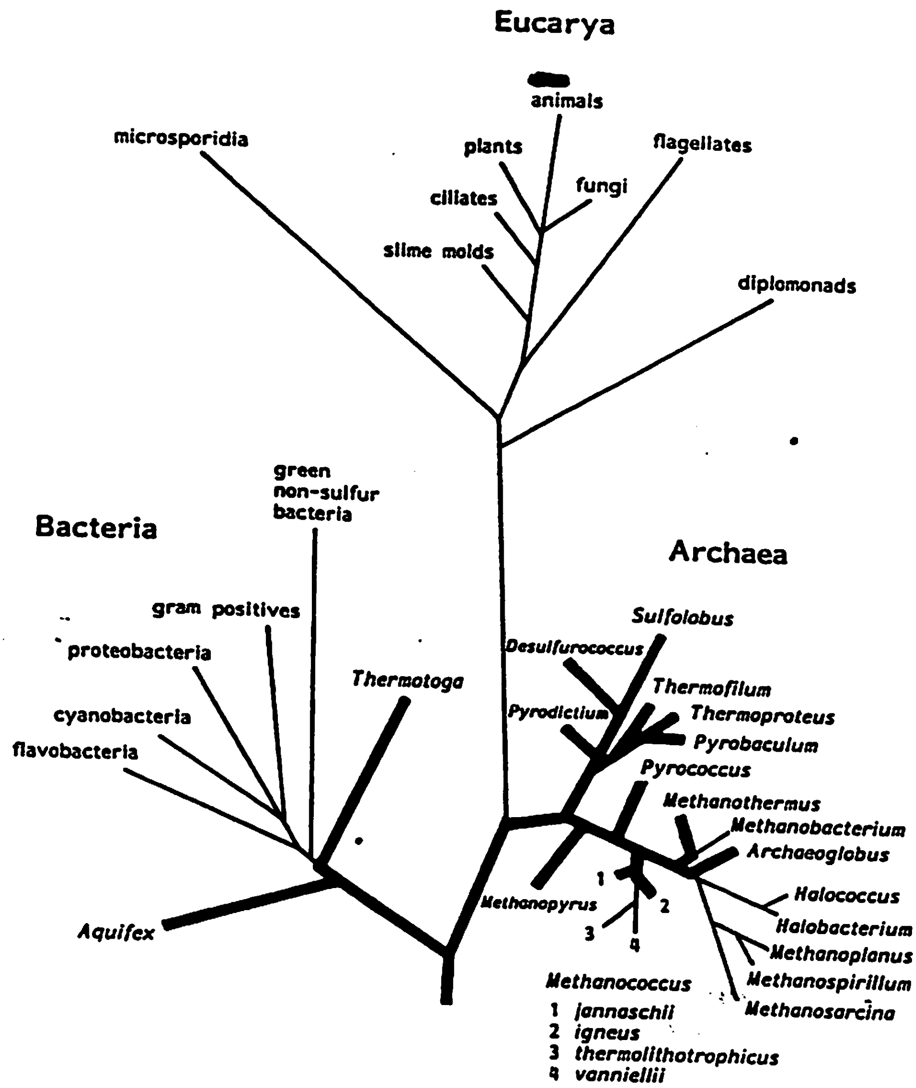


FIG. 3. Hyperthermophiles within the 16S rRNA-based phylogenetic tree. Redrawn and modified (based on C. R. Woese's model; Woese et al 1990, Blöchl et al 1995).

Comments:

(1) Position of thermophiles

(2) Rooting the tree

(3) Endosymbioses

(4) Behavioural & morphological diversity vs. metabolic diversity

Terminology

Mesophiles: 15-45° C

Thermophiles: 45-70° C

Hyperthermophiles: > 70°C (optima: 80-105)

(roughly)

e.g. Pyrodictium:

	min	opt	max
	82°C	105	110

A hot, deep biosphere?

Taylorsville Basin — soil: 10^9 culturable/g
— T.B: 10^4 "

2.8 km, 75 °C — Bacillus infernus

Most thermophilic organism known (199
lives up to 113 °C ~ 5 km down

How much biomass?

↳ down to 1 km depth

$M_{rock} \sim M_{oceans} \sim 10^{24}$ g

∃ $10^2 - 10^7$ bacteria/g in subsurface

1 μm bacterium ~ 4×10^{-12} g

⇒ $10^{14} - 10^{19}$ g bacteria (subsurface)

vs. 6×10^{17} g terrestrial biomass, 3×10^{15} g oceanic

Glaciers + Geysers = ??

or Why hot water and cold water don't mix

with your non-phreatic host, Andy Rivkin

1 Background, such as it is

Yellowstone National Park is the greatest concentration of hydrothermal areas in the world. It also suffered intense glaciation during the last ice age. A natural question follows: what happens when you park a glacier over a hot spring? Much of what follows is drawn from "Hydrothermal Explosion Craters in Yellowstone National Park" (which sorta gives away what can happen), by Muffler and others, in the *Geological Society of America Bulletin*, **82**, (1971). Other sources include "Effects of glacial ice on subsurface temperatures of hydrothermal systems in Yellowstone National Park, Wyoming: Fluid-inclusion evidence" by Bargar and Fournier (*Geology* **16**, (1988)), and "A Field-Trip Guide to Yellowstone National Park, Wyoming, Montana, and Idaho", USGS Bulletin 2099.

If we take the value for the present-day heat flux of the entire Lower Geyser Basin, this flux is sufficient to melt 3 meters of ice per year. However, this flux is not constant over the entire basin, but is rather concentrated in a few active areas with perhaps 10 times this average heat flow. In these places, aproximately 30 meters of ice per year can be melted. For that reason, lakes may have existed over hot spring areas while ice was still present in non-thermal areas.

In areas with high permeability, then, a glacier may move over a hot spring, be melted to a large extent, and have the water drop any sediment it was carrying, either remaining as a lake or continuing to move. The glacial sediment, now sitting over the hot spring, may be hydrothermally altered. When the glacier retreats, the landscape is left with topographic highs, hydrothermally altered. This is the case in the Porcupine Hills, which we may be able to see.

If there is low permeability, however, a different situation may evolve. As is explained by Cohen and Lorenz (both in this volume), under these circumstances normally a geyser would be found. What if you're under a glacier?

I'm glad you asked.

2 Hydrothermal Explosion Craters

Hydrothermal explosions (HTE) occur when water in near-surface rock at temperatures near 250 °C suddently flashes to steam with a enough power to disrupt rock. As mentioned above, this is due to the same instability and mechanism as geysers, simply much more violent.

It should be noted (I suppose) that these are not volcanic eruptions. The energy involved is stored as heat in water and rock within a few 100 feet of surface rather than in magma. This makes them different from maar craters, in which magma interacts with ground water.

Hydrothermal explosions (indeed, most of the hydrothermal systems discussed in this volume) occur because of an increase in the boiling point of water with increasing pressure. This results in sub-surface water temperatures increasing dramatically. This is unstable: high-density low-T water is above low-density high-T water. If near-surface permeability is high, as mentioned above, convection, circulation, and surface boiling occur, resulting in a hot spring. If near-surface permeability is low, steady-state processes are ineffective and a geyser may result.

And if you remove a whole bunch of confining pressure suddenly, everything goes boom.

Craters from HTEs range from 10s of meters to over a kilometer. HTEs are so violent, they disrupt confining rocks, expel lots of solid debris, and change the system. As a result, there's no short-term periodicity. HTE craters have been reported from Lake City, CA; Steamboat Springs, NV; Waiotapu, NZ; Tuscany, IT; and possibly on Iwo Jima and Noboribetsu, Japan. At Lake City, an innocuous set of hot springs suddenly erupted in 1951, giving rise to mud volcanoes disgorging 150,000,000 kilograms of mud, cratering 80,000 square meters, and showering fine debris 6 km away.

There are at least ten HTE craters in Yellowstone according to Muffler and others, 8 in cemented glacial deposits, 2 in ash-flow tuff, each with a rim of crater debris. The one we'll be seeing is in Pocket Basin.

3 Pocket Basin

At Pocket Basin, relations show an explosion occured during the waning stages of early Pinedale Glaciation. Muffler et al. suggest an ice-dammed lake over the hydrothermal system which suddenly drained, leading to an abrupt decrease in confining pressure → **KABLOOIE!!**

The Lower Geyser Basin, in which Pocket Basin is found, is filled by glacial and alluvial deposits. Pocket Basin is an oval area approximately 400 x 900 meters enclosed by a low ridge of explosion debris. The inner slope of the ridge is 20-25 degrees, outer slopes 10 degrees or less. The ridge is 4-21 m above floor, unconsolidated and unsorted. It's also unglaciated, but it *is* overlapped by outwash or alluvium, placing bounds on when things must have occurred. No bedrock ejecta can be found, so the explosion was entirely in rock at depths less than $\sim$ 45 m (in fact, bedrock rhyolite may have been too tough, stopping explosion). Debris found 1.2 km from center of basin, emplaced by air fall, though there is a possible mudflow in the northwest.

Rapid draining of glacial lakes by lifting, collapse or erosion of ice dams is common: Lake George in Alaska releases 0.6-2.5 cubic kilometers (!) of water in a few days, with the level of lake dropping 60 meters.

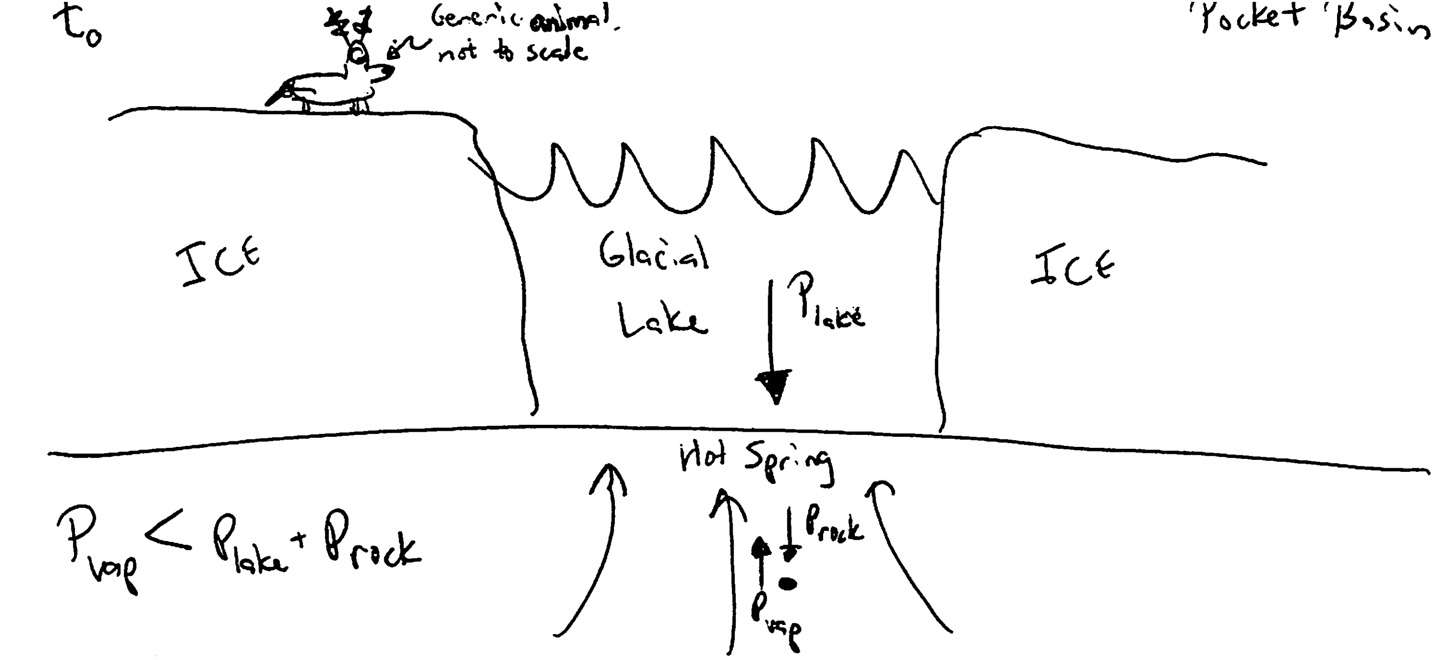
Muffler et al. assume a lake 130 m deep, with rapid draining. The pre-draining temperature profile in lake would be greatly superheated with respect to the new post-draining boling-point curve near the surface. To wit, the vapor pressure 30 m below surface would be 15.3 atm, vs. 7.7 atm lithostatic pressure. In fact, the vapor pressure would be higher than lithostatic pressure down to 100 m depth.

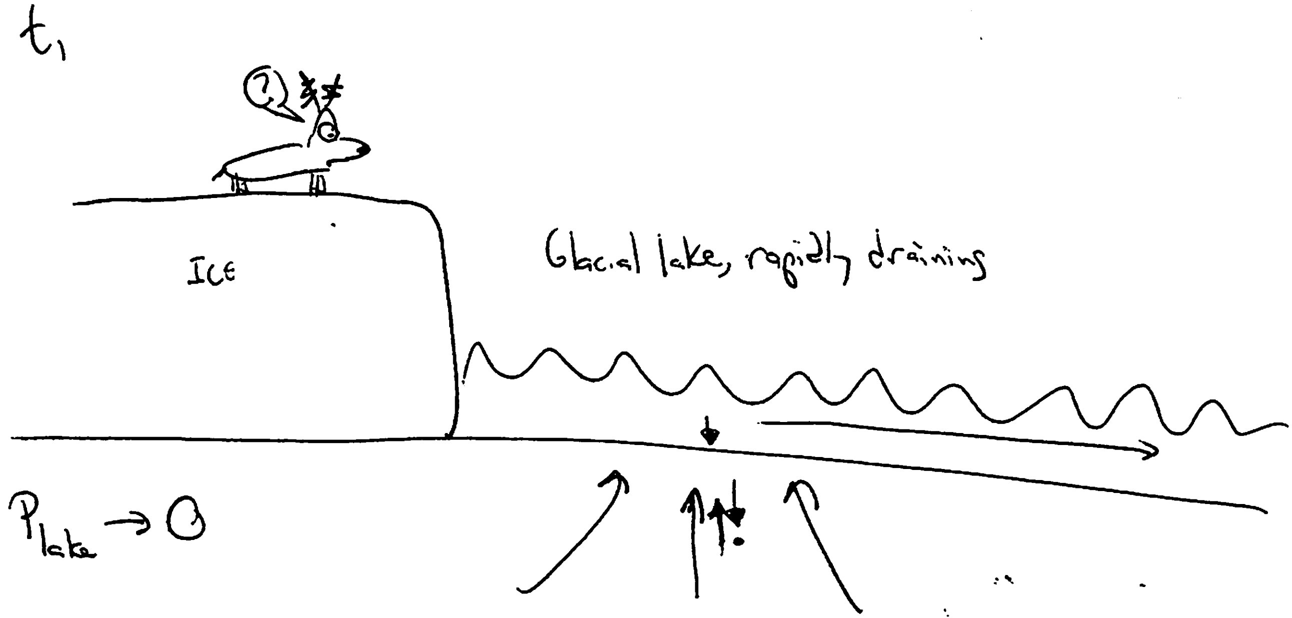
There are no flood deposits seen at Pocket Basin, but the putative lake may have been too small (1 square kilometer) to have them. Presumably most other glacial lakes in the vicinity had slow enough draining to allow an increase in hot spring and geyser activity to efficiently carry off the energy.

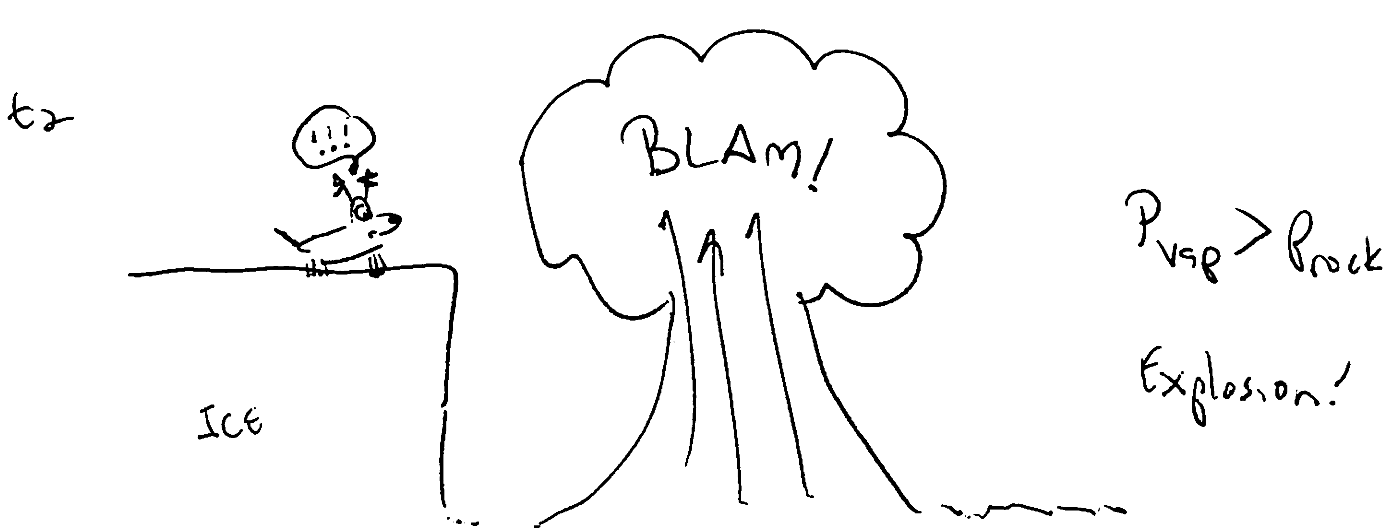
4 The Ever-Popular Planetary Connection

The most obvious extra-terrestrial site for possible HTEs (or glacial-hydrothermal interactions, more generally), is Mars. Evidence for glaciation, though controversial, has been reported by a number of authors. There is also evidence from the SNC meteorites that Mars (presumably the SNC parent body) has experienced some amount of hydrothermal alteration. Deposits like the Porcupine Hills would probably be difficult to identify as due to glacial-hydrothermal action from remote sensing. However, a HTE crater may be more easily identified. Unlike impact craters, these craters usually are not circular. Also, volcanic breccias are not found in them. An anomalous population of craters at the correct size in a glaciated area might be a good bet. I wouldn't lay odds, however.

Other than Mars, there are a few other candidate bodies for HTE craters. Counter-intuitively, they can be found in the asteroid belt. Although glaciation *per se* did not occur on these bodies, meteoritical evidence indicates that hydrothermal alteration did occur. Although alteration temperatures are relatively low on the asteroids, the outside pressure is extremely low ($\sim$ zero atm). It is plausible (far-fetched, maybe, but plausible), that an impact event early in solar system history on an asteroid experiencing hydrothermal alteration could bring an area with hydrothermal fluids close enough to the surface to cause an explosion. Similar mechanisms have been invoked to propose explosive volcanism on asteroids. Subsequent collisional evolution may make HTE craters difficult to study, however.


'Pocket' Basin
t_0
Generic animal, not to scale
ICE
Glacial Lake
P_{lake}
ICE
Hot Spring
P_{rock}
P_{vap}
$P_{vap} < P_{lake} + P_{rock}$


t_1
?
ICE
Glacial lake, rapidly draining
$P_{lake} \rightarrow 0$

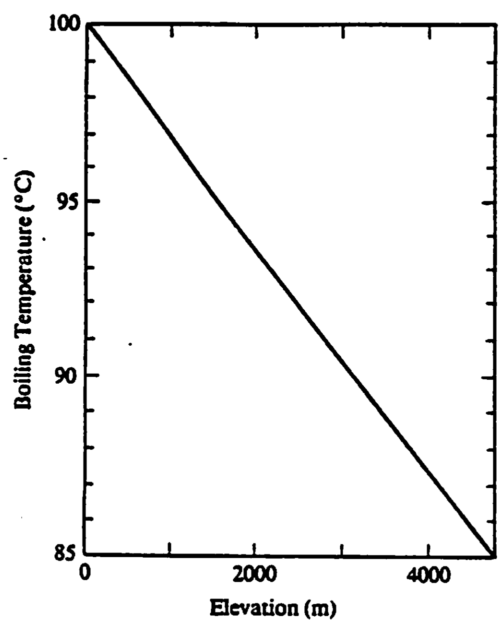

t_2
!!!
BLAM!
ICE
$P_{vap} > P_{rock}$
Explosion!

Physics of Geysers
Ralph Lorenz

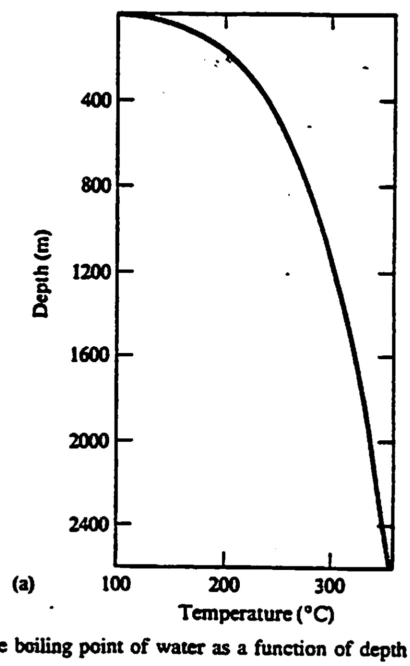
How do Geysers work, and why can't you make good tea in Yellowstone?

The conversion of a liquid into vapor happens continuously by evaporation, but is quickly limited by the build-up of a saturated layer immediately above the liquid. Evaporation can be accelerated by transporting the saturated vapor away, e.g. with a fan. Hence clothes dry faster on a windy day. However, if the temperature is sufficiently high that the saturation vapor pressure above the liquid exceeds the atmospheric pressure, boiling occurs and the vapor is transported by simply being pushed away.

The saturation vapor pressure is a strong function of temperature - for water the vapor pressure is about 20mb at 20C, and 1 bar at 100C. When the atmospheric pressure is lower than the sea level value, the temperature at which the svp equals ambient pressure (i.e. the local boiling point) is therefore lower too - at Yellowstone's elevation of 8300 ft, the boiling point of water is 93C.



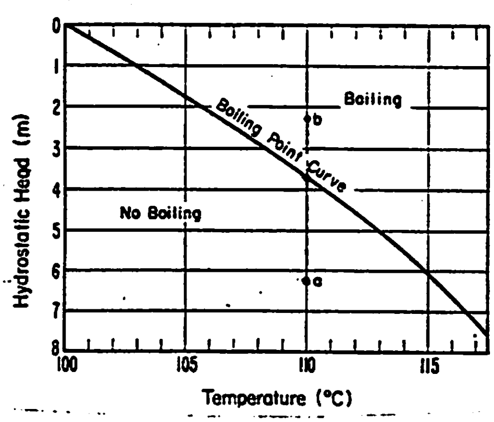
The boiling point of water as a function of elevation above sea level.



The boiling point of water as a function of depth of overlying water.

A corrolary is that it is impossible to heat water above this temperature in an open container. The brewing of good tea requires very hot (~100C) water, presumably because of Arrhenius kinetics in the solution of alkaloids in the leaves, thus (without using a pressure cooker) it is difficult, or at the very least rather slower, to make good tea in Yellowstone.

The pressure that must be exceeded for boiling need not be due only to a gas, but can be due to the hydrostatic pressure of overlying liquid(1 bar=760mm Mercury, or as scuba divers know, ~10m water). A 1m column of water increases the boiling temperature by about 3C. The pressure increment due to a column of liquid is often called the 'Hydrostatic head'.



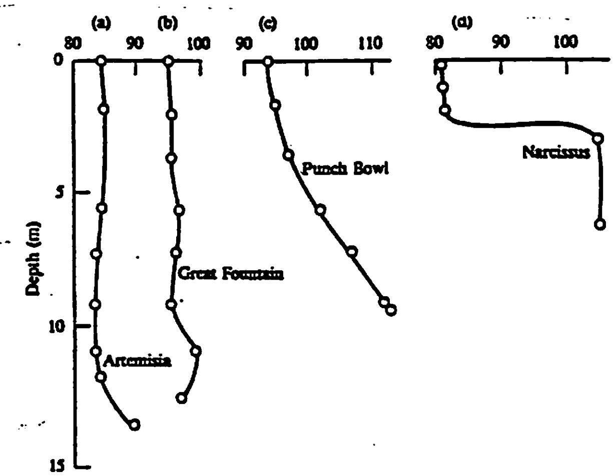


Figure 6-2. Temperature-depth curves for several types geyser reservoirs: (a) Artemisia, (b) Great Fountain, (c) Punch Bowl, (d) Narcissus, (e) Giantess, (f) The Great Geysir, and

Now consider taking a parcel of water at 8m depth at 116C, and imagine it displaced upwards by 2m (or, equally, consider removing the top 2m of the water column). Under the 6m column, the boiling temperature is now 115C rather than 118C at 8m, so the parcel begins to boil. As steam is much less dense than water, this boiling pushes the water column upwards. If the column of water exits a pipe - either into the open air, or into a pool whose diameter is much larger than the pipe, then the weight of the column is removed and the boiling temperature of the parcel falls yet further.

The formation of steam cools the liquid by removing latent heat. Exactly how much steam is produced (and ultimately, the exit velocity and therefore the eruption column height) depends on the enthalpy of the geyser waters i.e. their degree of superheating. A similar process to that described above can occur with gas-saturated hydrothermal fluids, since the solubility of many gases is pressure-dependent.

The temperature vs. depth characteristics, the means and rate of heat and liquid supply, and the plumbing details (e.g. one pipe, many pipes, connected chambers etc.) vary from geyser to geyser, and change the eruptive characteristics, but these, as they say, are

Who studied Geysers?

Geysers are doubtless well-documented, if only in a descriptive fashion, in Japanese and Icelandic literature, and Maori and native American legends. Written accounts in the West appear in the age of the gentleman-scientist, the early 1800s. Scotsman Lord Mackenzie toured Iceland in 1811 and proposed the first theory of geyser action, and Bunsen (yes, that Bunsen) made mineral and temperature measurements of the Great Geysir in 1847. Study of the Yellowstone geysers was somewhat hampered by the disbelief of the initial accounts from trappers and explorers - serious studies didn't happen until about 1870.

What makes Geysers tick, and what does it have to do with my eating and bathroom habits?

One of the enduring fascinations of geysers is their periodicity: prompting, for example, the name of 'Old Faithful'. Not all geysers are regular, and indeed the exact period between eruptions on regular geysers changes with, among other things, the tides, but by and large geyser eruptions happen on a remarkably regular basis.

Many phenomena in nature are periodic by virtue of a simple or damped harmonic motion - examples are pendulums, planetary orbits, springs etc. Regular events can also be generated by a continuous process balanced by a threshold-triggered process with hysteresis. Many biological processes (most obviously ingestion and excretion) are of this type, as are water clocks, and perhaps earthquakes. The hysteresis is required to prevent the system limiting itself at the threshold (e.g. eating a grain of sugar every minute instead of a larger amount 3 times a day)

Geysers are of this type - heat and/or hot water is injected somewhere in the system until the system reaches boiling point, then when it does, it erupts - removing all the heat in a short time.

Without hysteresis, if for example turbulent mixing driven by convection keeps the whole body of liquid at the same temperature, we have a continuously boiling spring or pool, and not a geyser. Condensation and bubble nucleation, however, are processes with significant activation energy, but once they occur are easy to continue. Friction, eating, going to the bathroom etc. are similar.

How does soaping a Geyser make it erupt ?

The activation energy of bubble formation, and hence the onset of boiling, is due to surface tension. A small amount of a surfactant such as soap reduces the surface tension and allows the easy formation of bubbles, thus removing some of the head above the waters and inducing eruption. The Great Geysir was triggered for the benefit of sunday visitors in this way in the early part of this century. A more environmentally-friendly way of stimulating geyser eruption is to use dry ice - this will form bubbles but without producing a scum deposit.

Geyser activity may be influenced also by tapping the water reservoir - one convenient Icelandic installation had a faucet from which a geyser could be turned from a continuous boiling spring into a gesyer and vice-versa.

What do Geysers have to do with Tucson thunderstorms, and how can a Geyser kill 1700 people in one night?

A related phenomenon to a geyser, and essentialy just a giant version of a gassy pool geyser, is the CO_2 driven lake eruptions , such as Lake Monoun and the tragic eruption of Lake Nyos in Cameroon (Zhang, 1996 and references therein) . This lake is fed by magmatic CO_2 at its base, and the CO_2 concentration in the lower depths built up to near saturation. Some perturbation, perhaps a sudden injection of more gas, or perhaps a thermal overturn,caused some CO_2-rich bottom water to rise within the lake. As it did so, the local pressure became lower than the local saturation pressure and CO_2 bubbles began to form. The bubbles made the water parcel more buoyant and continued the process.

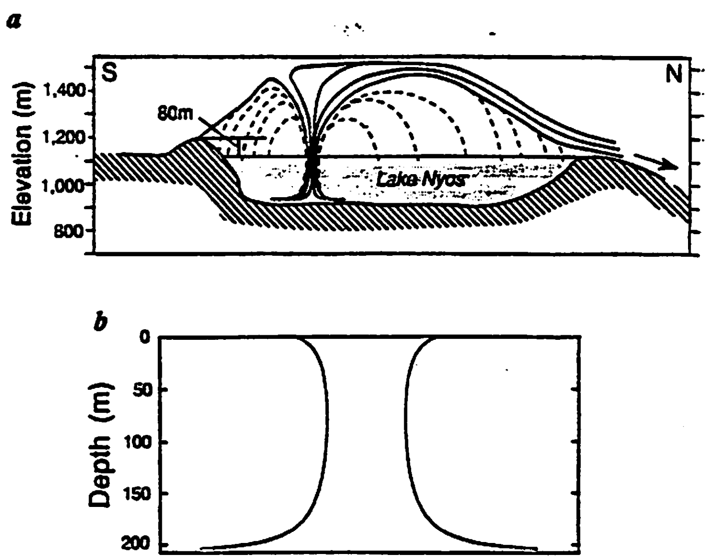
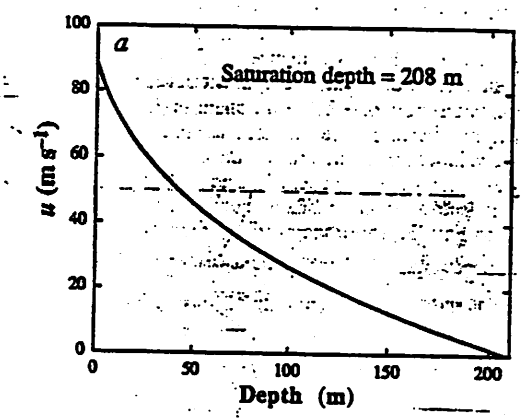


FIG. 1 a, Schematic south–north cross-section of Lake Nyos showing probable movement of gas cloud (solid curves) and water droplets (dashed curves) during a limnic eruption driven by CO_2 dissolved in the water. The trajectory of water droplets depends on their size; larger droplets rain down closer to the conduit. The vertical and the horizontal scales are the same. Turbidity of the flow is not shown. The position of the conduit is not important to the model presented and could as well be towards the north end of the lake[1]. The flow is shown as non-symmetrical because of possible wind. *b*, Close-up view of idealized erupting conduit shape, calculated by assuming that the mass flux is constant; that is, $A\rho u$ = constant = $(A\rho u)_{exit}$ where A is the cross-section area. The conduit diameter depends on the mass flux into it (hence no scale is given for the horizontal axis) and reaches a minimum at a depth of 77 m.

An analogue phenomenon is the formation of rain in cumulonimbus storm clouds - as warm, moist air ascends and cools, condensation is triggered. As condensation starts, it releases latent heat and promotes further vertical motion. Moist air is drawn in at the bottom and keeps the process going until the supply of moist air is exhausted.

The column of bubble-rich water is buoyantly accelerated upwards, and the eruption velocity at the surface depends only (assuming CO_2 saturation) on the depth of the lake. For an eruption from a depth of ~150m in Lake Nyos, the eruption velocity would be ~70m/s, reaching a height of 250m. A lower limit on the eruption column height of 120m was placed based on the distribution of dead animals. The eruption resulted in the injection of ~100 million kg of CO_2 gas over as long as 4.5 hours. The gas flowed downhill from the lake and suffocated the local village, with fatalities >1700. It is planned to reduce the danger of future eruptions by degassing the bottom waters by pipes (i.e. removing the activation energy from the process).



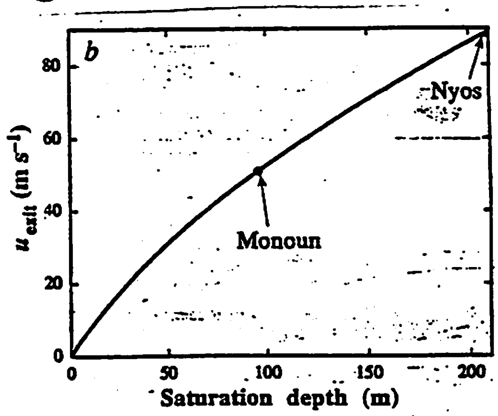


FIG. 2 a, Calculated maximum ascent velocity (u) of an erupting CO_2–water mixture as a function of depth for Lake Nyos. The calculation uses equation (3) with $\lambda = 0.87$ ($T = 23$ °C), $P_0 = 2.14$ MPa, $\rho_0 = 1{,}000$ kg m^{-3}, and pressure P in the conduit being hydrostatic. The λ value is calculated using the equation $\ln\lambda = 3.12272 - 4042/T + 911269/T^2$ (where T is in kelvin), derived from data in refs 20–23. The value of u is not strongly dependent on small variations of the atmospheric pressure. For example, changing the atmospheric pressure from 0.1 to 0.088 MPa (for an elevation of 1,100 m) changes u_{max} from 89 to 91 m s^{-1}. b, Calculated maximum exit velocity (u_{exit}) for CO_2-driven water eruption as a function of initial saturation depth using equation (3) with $\lambda = 0.87$ and $P = 0.1$ MPa. The u_{exit} for the eruption of bottom water of lakes Nyos and Monoun is indicated by arrows.

Could there be Geysers on other planets?

Why not? All that is needed is a fluid (or fluid mixture) with a boiling point near the ambient value, and an appropriate plumbing system. The Triton plumes (discussed elsewhere) may be due to geyser-like activity. It is possible to conceive of a Lake Nyos type event on Titan in ethane-methane-nitrogen lakes, if any of these is released from the subsurface.

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Y Zhang, Dynamics of CO2-driven lake eruptions, Nature 379, 57-59, 1996.

Earthquakes and Geysers

David A. Wood, Jr.

Hebgen Lake Earthquake (August 17,1959)

Yellowstone National Park is one of the most seismically active regions of the world. In August 1959, a large earthquake centered near Hebgen Lake, Montana jarred the entire park causing severe damage particularly in the western sections. In addition to the physical damage, the behavior of hot springs and geysers throughout the Firehole Basins was significantly altered.

Seismological Investigations

The Hebgen Lake earthquake (magnitude 7.1 as reported by the Pasadena Seismic Station) occurred just before midnight on August 17, 1959. The epicenter was located in Madison Valley about twelve miles north of West Yellowstone, Montana (Keefer, 1971) and the hypocenter was located 10 - 12 km below the surface (Murphy and Brazee, 1961). The earthquake was felt as far south as Utah and Nevada, as far north as British Columbia, as far west as the Pacific coast, and as far east as North Dakota--an area of nearly 2 million square kilometers (Murphy and Brazee, 1961)!

There were no foreshocks leading up to the Hebgen Lake earthquake but more than 1300 aftershocks had been recorded through October 15, 1959. Of these 1300 aftershocks, it is estimated that as many as 200 produced movement perceptible to humans. The main shock and four large (> magnitude 5.0) aftershocks originated along the Red Canyon fault just to the northeast of Hebgen Lake. Three other large aftershocks originated along the Madison Range fault to the northwest of Hebgen Lake (Murphy and Brazee, 1961).

At magnitude 7.1, the Hebgen Lake earthquake was the strongest earthquake to hit Yellowstone since the park was formed. However earthquakes with magnitudes > 4.0 occur in the park on a regular basis (on average at least one or two per year) and earthquakes with magnitude > 5.0 occur about once per decade. While the whole park is subject to earthquakes, the majority of them cluster in the southwestern and central sections.

Structural Damage

Most of the structural damage caused by the Hebgen Lake earthquake was fortunately confined to the area within 10 miles of the epicenter (Witkind, 1961b). Within the epicentral region, every building was damaged (some beyond any repair), bridges fell, highways were disrupted (with some sections falling into the lake), and pastureland was either badly fractured or inundated by water. Beyond about 10 miles from the epicenter, the damage diminished significantly. Chimneys collapsed, windows broke, and plaster fell, but most of the damage was reparable.

Of most concern was the stability of Hebgen Dam. For two days after the initial tremor, the entire town of Ennis was on a flood alert just in case the dam had broken (Witkind, 1961a). Fortunately, the dam, though cracked and damaged, held firm and the flood alert was rescinded.

The Human Story

In August 1959, the Hebgen Lake area was crowded with tourists as is typical during the summer months. Then, at 11:37 PM on the night of August 17, after most of the residents and tourists had gone to bed, the first earthquake shock hit. Estimates of the tremblor duration ranged from five seconds to several minutes; but to the frightened victims, it must have seemed much longer. Here are some excerpts of their stories.

> All of a sudden, the trailer began to shake violently up and down and back and forth. I thought at first that Jack was fooling around and shaking the trailer, but in a split second I looked around and saw: water pouring out of the wash basin; all dishes, groceries, and clothes falling out of the cabinets; and the gasoline lantern swinging in a two-foot circle and looking like it would fall any minute.
>
> \- Mrs. Jack B. Epstein

> I went to sleep about 9:30 PM and was awakened by the frenzied jiggling of the trailer. Things were falling from shelves all over the place. I thought the trailer had come off its jacks, jumped the chocks, and was rolling down the hill. I scrambled out the front door determined to stop the trailer, no matter what, although I had no idea as to how I would go about it. When I got outside, the trailer was in place but the trees were whipping back and forth and the leaves were rustling as if moved by a strong wind-but there was no wind. I could hear avalanches in the canyons behind me, and could see huge clouds of dust billow out of the canyon mouths. Jack Epstein who was awake at the time of the earthquake says he heard a deep rumbling in the Earth. I drove down the hill toward the [Blarneystone Ranch]. About a quarter mile from camp, I came upon a large new fault scarp that cut across and displaced my access road.
>
> \- Irving J. Witkind

Other people told frightful tales of floods caused by water splashing over the top of Hebgen dam and of landslides that buried cars and claimed lives. By the morning of August 18, nine people had died as a result of the earthquake and to this day, nineteen more are missing and presumed dead.

Alteration of Geyser Patterns

The Hebgen Lake earthquake did more than just damage buildings and scar the surface; it also altered the behavior of hot springs and geysers throughout the region. Most significantly affected were the geysers of the Firehole basin.

Summary of Alterations

The most commonly observed changes in active geysers as a result of the earthquake were usually a rise in the water temperature and an increase in the turbidity of the water. Further, many geysers that had erupted on a regular schedule prior to the earthquake began erupting more frequently. In other cases, active geysers became dormant and some dormant geysers erupted for the first time in hundreds of years. At least one new geyser was created as a result of the new eruption. It is aptly named "Earthquake Geyser" and is found in the Sprinkler Group in the Lower Geyser basin (Marler, 1961). Table 1 (reproduced without permission from Marler, 1961) summarizes the state of thermal activity immediately after the Hebgen Lake earthquake.

Hypothesis

The plumbing of hot springs and geysers passes through layers of glacial gravel which are very susceptible to earthquakes. When an earthquake occurs, the gravel may be loosened, compacted, or shifted. If an earthquake is large enough to shift significant amounts of gravel, then the plumbing beneath a hot spring can be significantly altered. Dormant geysers might suddenly re-erupt if the material that had once blocked the passageway were removed. A partial increase or decrease in thermal activity might be the result of partially opening or closing a particular channel. Further, the murkiness of eruptions immediately following an earthquake may be the result of loosened gravel caught in the water flow being forced to the surface.

The earthquake itself may also fracture the gravel layer(s) or the underlying bedrock, creating new waterways where none had existed before. If the fractures reach the surface then it is possible to create a new geyser where previously none had existed. New fractures in the plumbing may also explain the subsidence of water levels in the region immediately after the earthquake. As new fractures are created, more water can be contained in the plumbing. More water in the plumbing means a greater discharge volume in an eruption and the higher pressure in the plumbing system due to the added water may be partially responsible for the subsequent rise in water temperature.

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Figure Captions

Figure 1: Map of the Lower Geyser Basin. Note the Location of Earthquake Geyser in the Sprinkler Group and the nearby Kaleidoscope Group. Earthquake Geyser was formed in the Hebgen Lake Earthquake and the Kaleidoscope group suffered significant alterations as a result of the earthquake.

Figure 2: Map of Yellowstone National Park showing the locations of the August 17, 1959 and June 30, 1975 earthquakes.

Figure 3: Simple diagram of the sub-surface plumbing of a geyser and a hot spring. During an earthquake the sand and gravel may shift altering the plumbing system or new fractures may be created opening new channels which may create new geysers or hot springs.

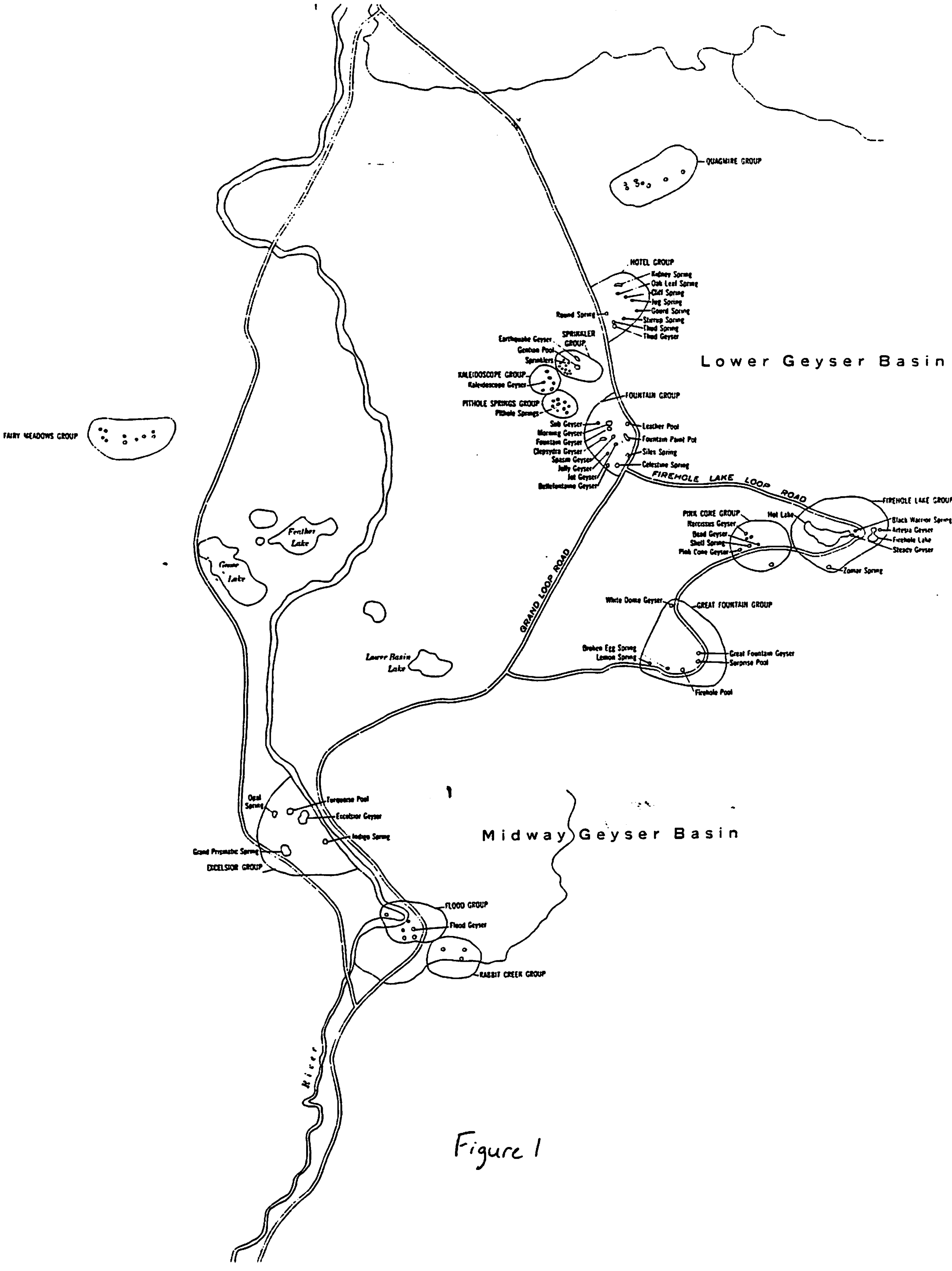
QUAGMIRE GROUP
HOTEL GROUP
Kidney Spring
Oak Leaf Spring
Cliff Spring
Jug Spring
Gourd Spring
Stirrup Spring
Thud Spring
Thud Geyser
Round Spring
Earthquake Geyser
SPRINKLER GROUP
Gentian Pool
Sprinklers
KALEIDOSCOPE GROUP
Kaleidoscope Geyser
PITHOLE SPRINGS GROUP
Pithole Springs
Lower Geyser Basin
FOUNTAIN GROUP
Sub Geyser
Morning Geyser
Fountain Geyser
Clepsydra Geyser
Spasm Geyser
Jelly Geyser
Jet Geyser
Bellefontaine Geyser
Leather Pool
Fountain Paint Pot
Silex Spring
Celestine Spring
FIREHOLE LAKE LOOP ROAD
FIREHOLE LAKE GROUP
Hot Lake
Black Warrior Spring
Artesia Geyser
Firehole Lake
Steady Geyser
Young Hopeful Geyser
PINK CONE GROUP
Narcissus Geyser
Bead Geyser
Shell Spring
Pink Cone Geyser
Zomar Spring
FAIRY MEADOWS GROUP
Feather Lake
Goose Lake
GRAND LOOP ROAD
White Dome Geyser
GREAT FOUNTAIN GROUP
Broken Egg Spring
Lemon Spring
Great Fountain Geyser
Surprise Pool
Firehole Pool
Lower Basin Lake
Opal Spring
Turquoise Pool
Excelsior Geyser
Indigo Spring
Grand Prismatic Spring
EXCELSIOR GROUP
Midway Geyser Basin
FLOOD GROUP
Flood Geyser
RABBIT CREEK GROUP
River

Figure 1

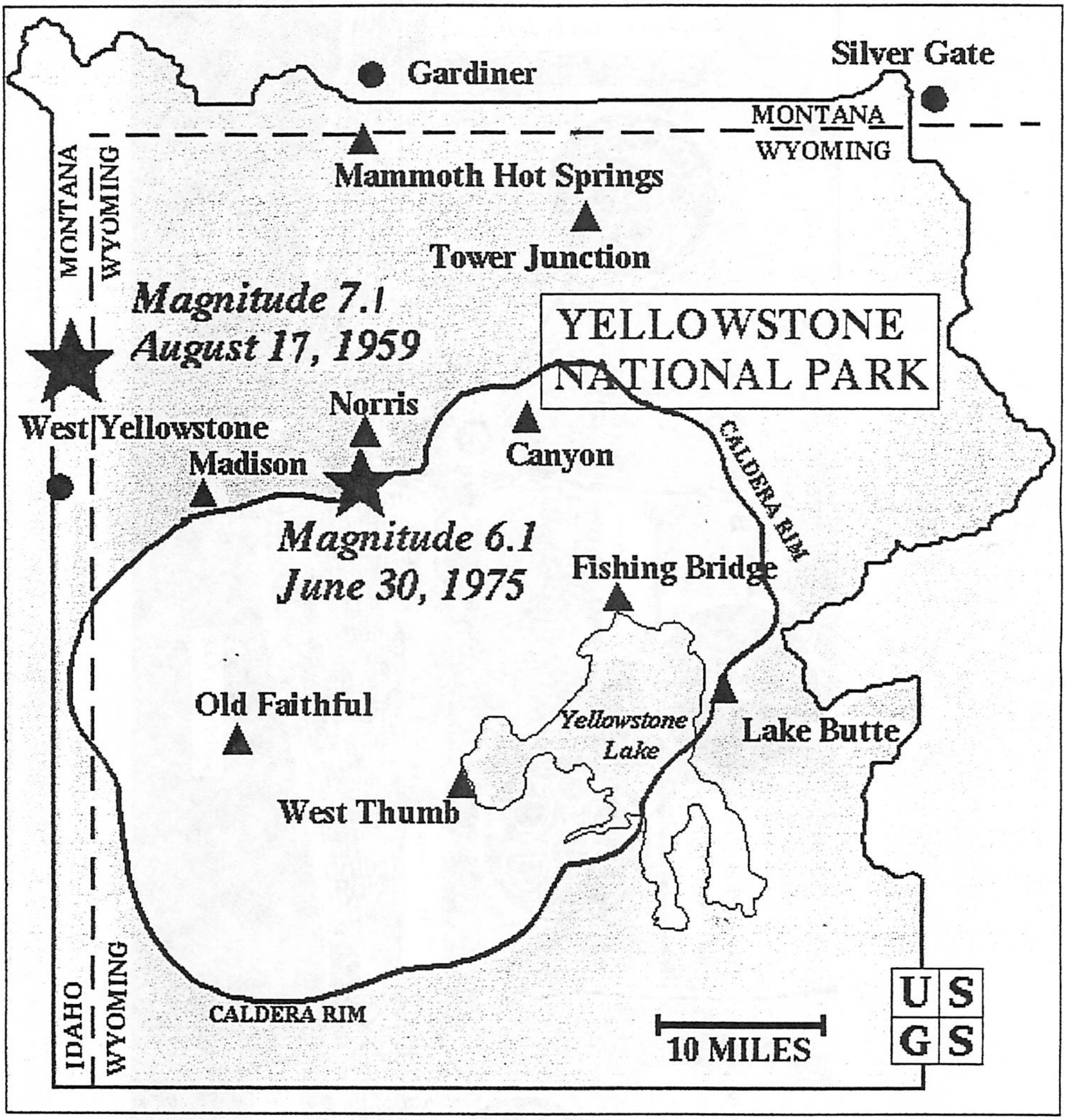
Gardiner
Silver Gate
MONTANA
WYOMING
Mammoth Hot Springs
Tower Junction
MONTANA
WYOMING
Magnitude 7.1
August 17, 1959
YELLOWSTONE
NATIONAL PARK
West Yellowstone
Norris
Madison
Canyon
CALDERA RIM
Magnitude 6.1
June 30, 1975
Fishing Bridge
Old Faithful
Yellowstone
Lake
Lake Butte
West Thumb
IDAHO
WYOMING
CALDERA RIM
10 MILES
USGS

Figure 2

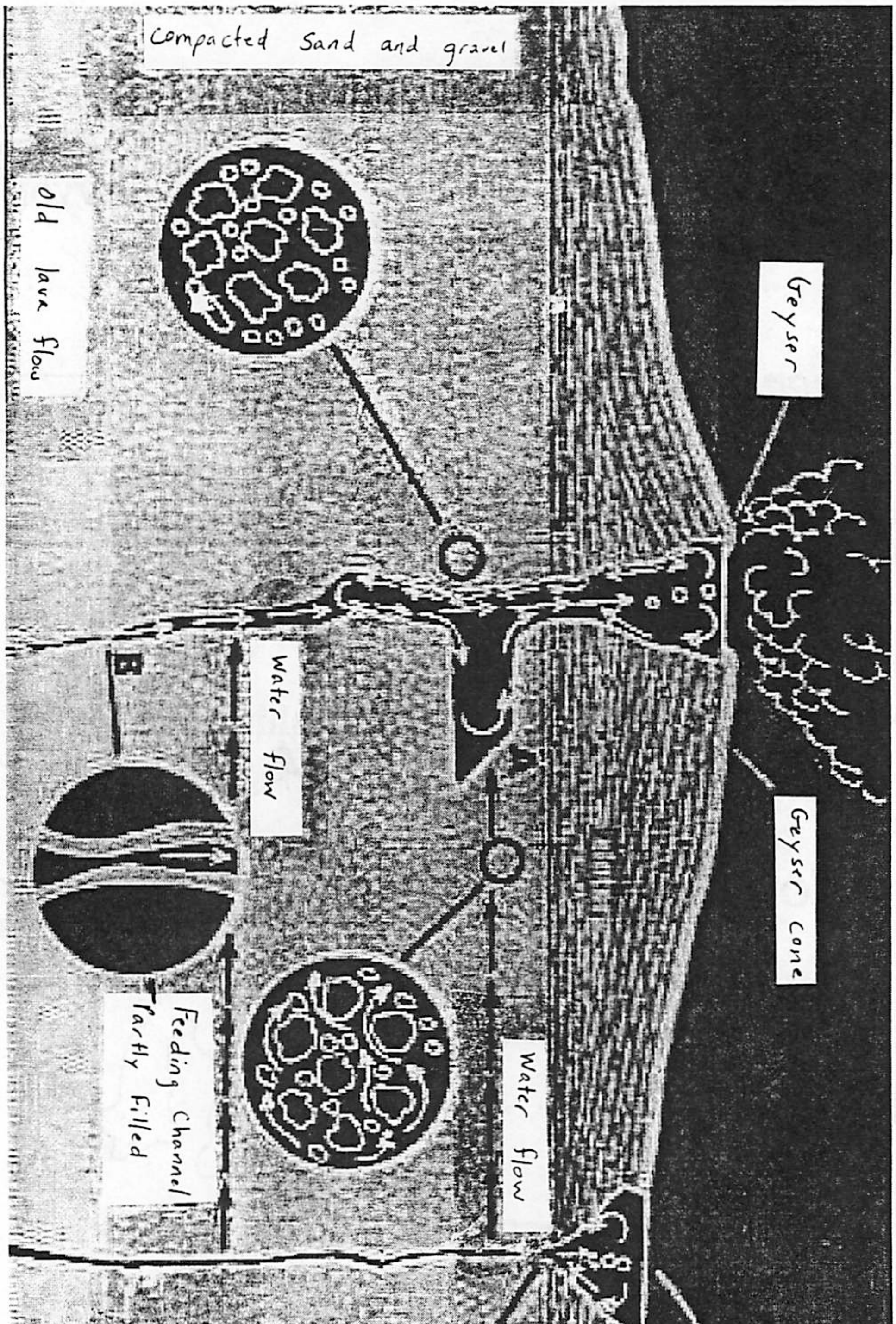
Compacted Sand and gravel
Geyser
Geyser cone
Hot Spring
old lava flow
Water flow
Water flow
Feeding channel partly filled
Feeding channel nearly filled with minerals
old lava flow

Figure 3

Planetary Plumes or Geysers

Greg Hoppa

During this field trip we will have the opportunity to study geysers. While others will address the special plumbing and hydro-thermal system required for geysers on the earth, we must also discuss the other planetary bodies which may also exhibit geyser-like activity. Io and Triton could easily fit this scenario while Europa and Titan could also be candidates for places with possible geysers now or in the past.

Io:

In 1979 Voyager 1 observed nine active plumes on the surface of Io. Four months later, Voyager 2 observed eight of the nine plumes detected by Voyager 1 that were still active [7]. Two types of plumes on Io have been identified [4]. The first is a Prometheus-type plume which is typically 50 -200 km in height and 150-500 km in diameter at the base suggesting eruption velocities on the order of 500 m/s. The eight plumes observed by both Voyager spacecraft fit into this category suggesting that plumes of this nature could be active on time scales of months to years [4]. Promethus has been active during the entire time that Galileo has been in orbit around Jupiter [5]. Figure 1 is a Galileo image of Io which shows Prometheus near the terminator and Pillan patera erupting near the limb.

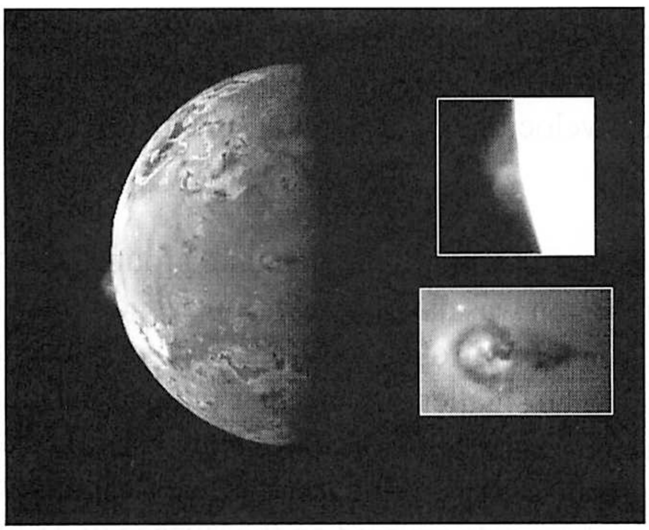

Figure 1. Galileo image of Prometheus and Pillan Patera.

Pele type plumes are much larger in scale over 300 km in height and 1200 km at the base. Only 3 Pele type plumes have been characterized on the surface (Pele, Surt and Aten) and of those three only Pele was observed in eruption[4]. Surt and Aten were active during the time between Voyager observations, suggesting that these plumes are relatively short lived[4]. Figure 2 shows Pele as observed by Voyager 1, Voyager 2, and Galileo respectively.

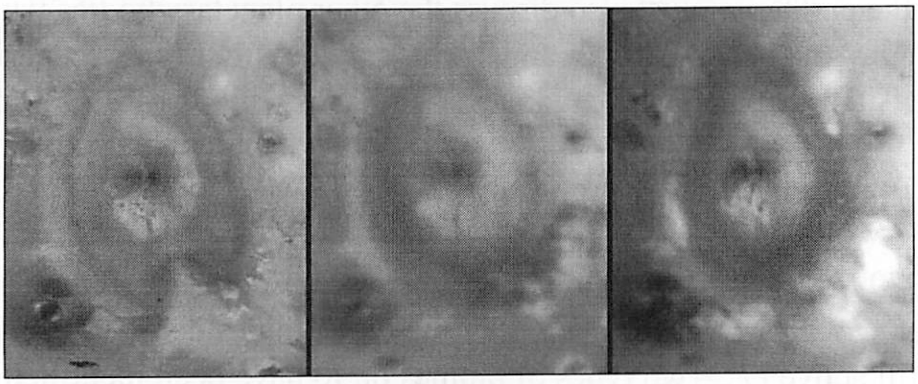

Figure 2. Pele

All plumes on Io detected by both Voyager and Galileo are associated with hot spots[6]. High temperature hot spots on Io are greater than 500 K and could be as high as 1500 K to 2000 K suggesting that the volcanism on Io is dominated by silicate magmas, not sulfur and sulfur dioxide[6]. In this case the sulfur and sulfur dioxide plumes associated with hot spots may be similar to terrestrial geysers. Near hot spots sulfur dioxide could be heated at depths around 1.5 km, producing SO_2 vapor and causing the vapor and liquid to move upward. The upward motion causes more SO_2 to vaporize and accelerate toward the surface where it nears its triple-point and explodes near velocities of 500 m/s.

Triton:

Before the Voyager encounter with Neptune, ground based observations of Triton predicted that if Triton was dark enough (low albedo) the surface temperature may be near the triple point of nitrogen (63 K). However, preliminary Voyager images revealed Triton to be smaller and brighter (albedo 0.7) than expected, indicating a frigid surface temperature of 38 K. The possibility of an active surface dropped rapidly with the discovery of the low surface temperature.

Two active plumes were discovered on the surface of Triton by using stereo pairs of the surface[9]. Two images taken from different perspectives were laid on top of one another. The material on the surface of Triton registered in the two images, but the material aloft in Triton's atmosphere did not completely register, thus leading to the discovery of two plumes. Figure 3 shows the two active plumes discovered by Voyager 2.

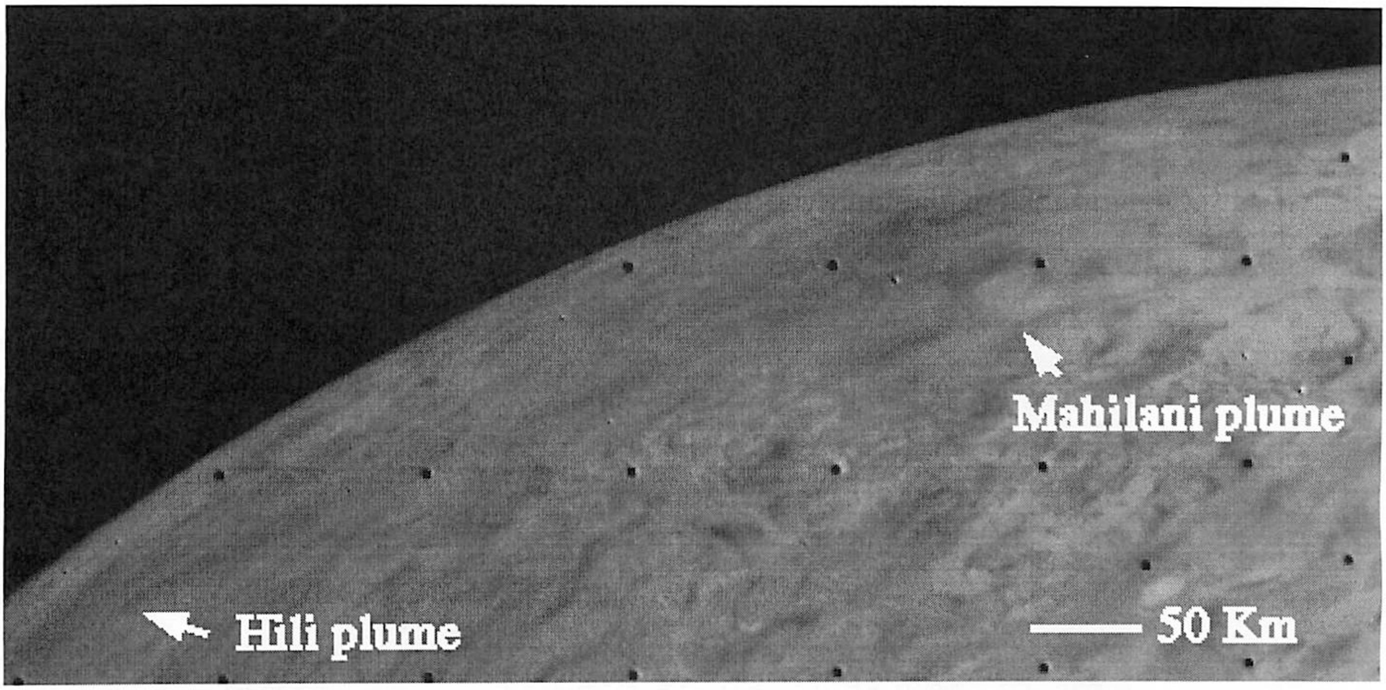

Figure 3. Best Voyager image of both plumes (Resolution 1.2 km/pix)

The plumes rise about eight kilometers into the atmosphere and then are blown downwind [9]. Based on changes of features in the plumes over the observing sequence the wind velocity was estimated at 15 m/s at an altitude of 8 km [9]. Near the surface the plumes appear nearly vertical, suggesting the eruption velocity must be substantially higher than any wind on the surface [9]. Estimates for the size of the vent range from 20 m to 2 km.

A solid state greenhouse effect could be one possible model for the formation of plumes on Triton [1]. In this model the surface of Triton is covered by a thin transparent layer of solid nitrogen with some organic material at its base. The absorption of sunlight by the darker material will result in an increase in the temperature relative to the surface and an increase in the vapor pressure of the nitrogen. As the pressurized nitrogen is vented toward the surface, the some of the darker organic material would also be ejected into the atmosphere. Other possible models for the plumes on Triton include dust devils, methane plumes, melting of a permanent nitrogen polar cap, or out-gassing of the ice mantle [3]. While the solid state greenhouse model appears to be the current favorite model, the plumes may have little or no relation to terrestrial geysers, in the sense that geysers on earth rely on a steady geo-thermal heat source, not solar energy. Terrestrial geysers have two discrete components the water and the rock, not the mix of nitrogen and methane that is believed to take place on Triton.

Europa:

Based on Voyager and Galileo images, cryovolcanism and geysers have been suggested as possible processes taking place on the surface of Europa [2]. One possible location is Rhadamanthys Linea shown below in figure 4.

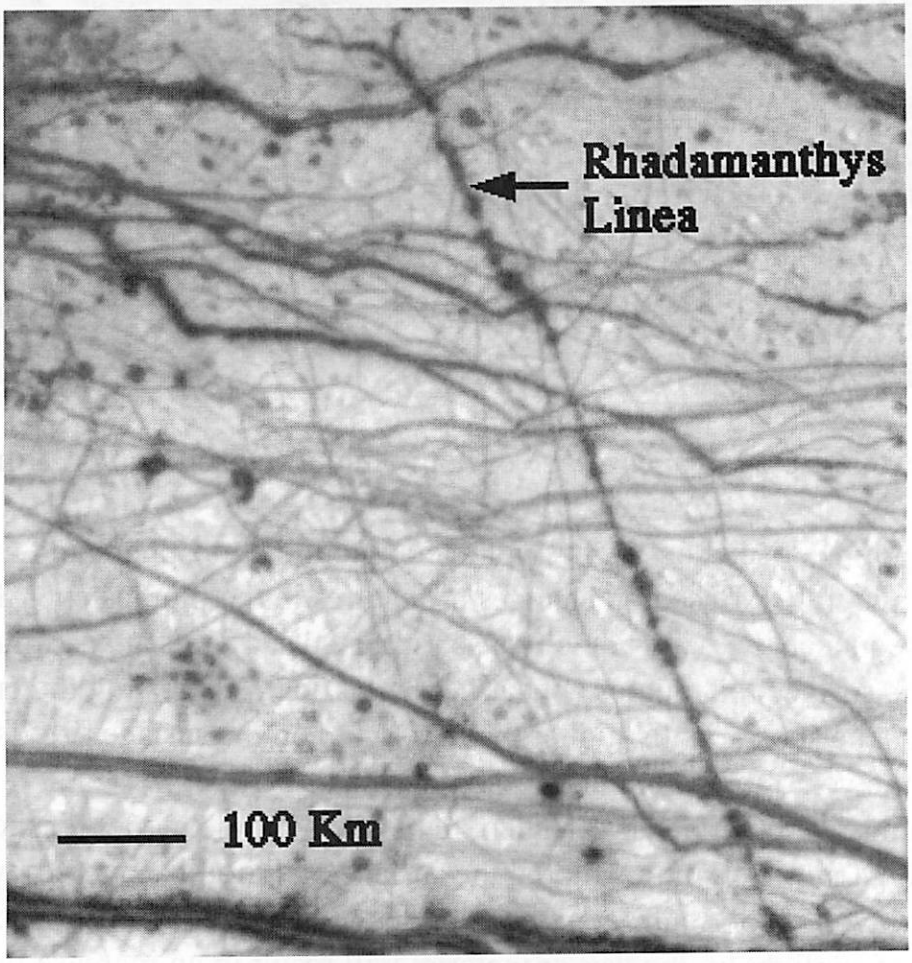

Figure 4. Galileo image of Rhadamanthys Linea (Resolution 1.6 km/pix)

If geysers do exist on Europa, there must be some very interesting geology taking place there. Most of Europa's surface is believed to be water ice. Due to the fact that liquid water has a greater density than ice, liquid water will not naturally want to erupt on the surface of Europa. However, depending on the temperature, it can re-freeze rather quickly. Fagents and Greeley would argue that the circular features around Rhadamanthys Linea are a result of explosive venting on Europa [2]. There are places on the surface of Europa that appear to have been melted [8]. Most likely at this time the water boiled quickly until new ice was formed, but vigorous boiling of water at the surface is not a geyser or explosive venting. Furthermore, if Europa was actively spewing water 27 km [2]above the surface then Europa should have a more substantial atmosphere (containing the CO and CO_2 volatiles required by their model) than the tenuous oxygen one that is observed there. Current Galileo observation plans for the GEM extended mission include one orbit to look for possible geysers over Rhadamanthys Linea and Agenor Linea. However, on Galileo's 24th orbit the spacecraft will encounter Io at a range of 500 km. At this time Galileo will be over Pele, and perhaps the particles and fields experiment will obtain the first direct measurement of a portion of Pele's plume.

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Geothermal Energy: the Cure for the Energy Crisis! *

(or is it?)

Robert F. Coker

I. The Earth is Dying!

Turn up your heaters! Destroy all air conditioners! Save the Earth! The Earth is cooling, having lost about 10% of its initial heat to space; net loss at the moment is about 10^{13} W. The Earth will eventually be a cold dead body like the Moon – but this will occur long after the Sun has boiled away the oceans so I guess we needn't worry about it. Since the Earth is cooling, clearly there's a temperature gradient present (about .03 K/m for the crust), so why don't we use it? Well, we are – about 10^{10} W of the Earth's lifeblood are being 'used' by people today. Not too bad (.1%) when you consider how difficult it is to heat a greenhouse with an erupting volcano (productively, that is). Using this heat is fairly easy: just find a 'hot spot', drill down a few kilometers, lay a pipe, install a pump, and use the resulting hot water and/or steam for whatever you want. Some of the many uses to which hot water/steam can be put are listed in Table 1. Of course, you need to find a hot spot first – luckily, most countries have at least some geothermal resources (in fact, many developing countries have no other natural energy source).

II. Now for the Bad News

First off, drilling is expensive (about $ 1 million per well). Geothermal drilling is generally as deep as oil drilling (a few km) but requires larger well casings. Good quality stainless steel piping is required too. Second, there is the nasty stuff that is mixed in with the hot water and steam: CO_2, SO_4, H_2S, Cl, F, B, As, Hg, Pb, and silicates to name a few. In some places (Italy) these nasties are reclaimed and used; in other places (California),

* WARNING – not to be taken internally (except in Iceland)

they are deposited in waste ponds; in yet other places (Japan), they are re-injected into the ground (at great expense). Only Iceland is lucky enough to have geothermal waters that are pure enough to actually be potable. Thus, in most cases, pipe and container corrison and scaling are big problems. And the rotten-eggs smell (not to mention the noise of venting steam) coming from geothermal power plants doesn't make them attractive neighbors. Third, there's the problem of location. Porting large volumes of hot, mineral-rich water over large distances is quite difficult and expensive. This limits use of geothermal energy to within a few tens of kilometers of the well site. High temperature (> 150 °C) sources are rare but low temperature (20-80 °C) water sources can be found practically all over the world (*e.g.* Arizona has the largest potential for geothermal aquaculture in the world). Fourth, there is the age-old problem of funding. After the energy crisis passed (which, according to the US Gov't, it did in the mid '80s), federal support for geothermal energy projects essentially dried up (can we say 'oil' boys and girls? I knew we could). Lastly, geothermal energy (in the form of heated water) is NOT a renewable resource. The hot steam wells (used for electricity) can dry up over just a few years; new wells need to be drilled fairly often. Eventually, the entire reservoir can be drained dry (happened in California). Even with re-injection of the fluid, the timescale for replenishment of the reservoir is longer than the lifetime of any investor.

III. Electricity Generation is Even Harder

To make a conventional turbine geothermal power plant is more expensive than any other type of power plant (except nuclear of course). Although maintenance costs are fairly low and the fuel is free, it takes years for a plant to start making a profit. If the well pressure drops (to drive a turbine, about 10 kg/s of steam at more than 10 atmospheres is generally needed), the plant may have to close before ever getting into the black. And since geothermal prospecting is an inexact science (ahem), the gamble involved is huge (rough cost for a MW plant is $5 million). With recent advances, a new type of portable power plant (a 'binary plant') has been developed that needs only 85 °C water; this allows more locations to use geothermal power and lengthens the lifetime of a given well. Unfortuntely the cost is presently fairly prohibitive, requiring a few decades to reach profitability. Yet another kind of plant is under development (has been for 20 years) that doesn't require a natural reservoir but only 'hot rocks'. It entails drilling a hole, injecting water to fracture the rock and create a reservoir, and drilling another hole to pump up the heated water. Without further technological developments, however, geothermal power generation is not going to be a growth industry (power plants that are coming online are barely keeping up with the loss of older plants).

Interestingly, the technology developed so far for geothermal power has been used by non-geothermal power companies to increase their power output. Since the main problems with geothermal sources (cost of drilling, nasties in the fuel, and variable water/steam pressure) don't apply, they have added secondary plants that use the waste heat from say a coal plant to increase output by a few percent.

IV. Other Uses

There are a lot of other uses for hot water listed in Table 1. And here is the true benefit of geothermal energy: many of these uses can be cascaded together. For example, say you are lucky enough to have a 100 °C fairly high pressure well. First, you run it through a binary power plant (maybe removing some salts along the way). Then you could run it through a greenhouse so you could grow tomatoes year round (Iceland does this). Next you could use the water (now at around 40 °C) to heat the soil (extends the growing season), make a hot spa, or heat a pool. Finally, the water could be used to keep a fishing hatchery at just the right temperature for maximum yield (fish are quite sensitive to temperature). Most geothermal locations aren't likely to yield enough steam to drive a power plant but most other non-industrial uses are likely to be available (and you won't have to drill so deep to get it). Recent geoprospecting surveys suggest that hundreds of communities in the Western US are sitting on geothermal resources of this nature.

There are other ways to take advantage of the thermal properties of the Earth. In the Netherlands, for example, excess energy from solar panels is stored in the form of hot water kept 100s of meters below ground. The hot water is then used for heating in the winter. During periods of low demand, similar methods could be used to store surplus energy from conventional power plants and then retrieve it at peak demand times.

It is perhaps a testament to the status of geothermal energy to note that more than half of the economic value of the geothermal industry is in tourism and balneology. And, just to end on a cynical note, most of the public land in the US that is thought to harbor high temperature geothermal reservoirs has been bought by the oil companies.....

V. Table 1

Temperature	Some Uses
180 °C	Paper pulping
170	Separation of heavy water; diatomaceous earth
160	Drying of fish and timber
150	Making of Alumina; conventional power plants (lower limit)
140	Food drying and canning
130	Sugar refining; salt extraction
120	Distillation of fresh water
110	Cement manufacturing
100	Wool washing and drying
90	De-icing
85	Binary power plants (lower limit)
80	Space heating (lower limit)
70	Regrigeration (lower limit)
60	Animal husbandry; greenhouses (lower limit)
50	Mushroom growing; hot spas
40	Soil warming
30	Swimming pools; biodegradation and fermentations
20	Aquaculture

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High temperature ecosystems and their chemical interactions with their environment.

Jorge Adrian Pastoriza

High temperature ecosystems are defined as those developing at temperatures in excess of 60°C, even though some community members have a wide temperature range of tolerance and grow well below 60°C. Although hot springs > 60°C account for less than one in 10^6 of the earth's springs, they are widely distributed and found on all of the continents, including Antarctica. There has been much interest in high temperature ecosystems and they have been well studied at Yellowstone.

Interactions between the microbes and their environment, are chemical and physical. The former may produce chemical changes in the molecular flux, and the latter through physicochemical properties of the cell surface what is often important in promoting the nucleation of minerals.

In phototrophic thermal ecosystems, there is little or no net accumulation of reduced carbon and a quasi-equilibrium is established between the synthesis and oxidation of reduced carbon. Uptake of carbon dioxide by phototrophs is favourable to calcium carbonate (travertine) deposition. Thermal systems also contain chemolithotrophs and sulfate reducers, potentially capable of depositing carbonate. If hydrothermal deposits occur on Mars, the distribution of travertine is likely to be restricted if there is a lack of pre-existing sedimentary carbonate. Less biologically interactive deposits of silica and ochre may predominate.

TABLE 1 Potential chemical interactions between microorganisms and hot-spring deposits

Mineral	*Microbial reactions significant in mineral deposition/dissolution*	*Participating microbes*
Aragonite/calcite $CaCO_3$ (precipitation/dissolution)	$Ca(HCO_3)_2 \rightarrow CaCO_3 + H_2O + CO_2$	*Synechococcus, Oscillatoria terebriformis, Fischerella laminosus, Chloroflexus, Hydrogenobacter thermophilus, Methanobacterium, Thermothrix, Thermoproteus*
	$CaSO_4 + 2(CH_2O) \rightarrow CaCO_3 + H_2O + CO_2 + H_2S$	*Desulfovibrio, Clostridium thermohydrosulfuricum*
	$Ca(NO_3)_2 + 3H_2 + C$ (organic) $\rightarrow CaCO_3 + N_2 + 3H_2O$	*Bacillus thermophilum*
	$2NH_3 + 2H_2O + Ca(HCO_3)_2 \rightarrow CaCO_3 + (NH_4)_2CO_3 + 2H_2O$	Ammonia producers, ?*Pseudomonas*
	$(CH_2O)_n$(organic matter)$+ O_2 \rightarrow CO_2 + H_2O$	*Synechococcus, Oscillatoria, Thermus*
Silica (hydrated) $SiO_2\,nH_2O$ (precipitation/dissolution)	$CO_2 + H_2O \rightarrow HCO_3^- + H^+$	*Desulfovibrio*
	$CO_3^= + H_2O \rightarrow HCO_3^- + OH^-$	Photosynthetic alkalization
Goethite FeO OH	$Fe^{2+} \rightarrow Fe^{3+}$	Iron-oxidizers, ?*Thiobacillus*
	$Fe^{3+} + H_2O \rightarrow FeO\,OH$	
Gypsum $CaSO_4$	$Ca^{2+} + S + 2O_2 \rightarrow CaSO_4$	*Chromatium, Desulfovibrio*
Limonite $Fe_2O_3\,nH_2O$	$4Fe^{2+} \rightarrow 4Fe^{3+}$	Iron oxidizers ?*Thiobacillus*
	$4Fe^{3+}3O_2 + H_2O \rightarrow 2Fe_2O_3nH_2O$	
Manganite MnO OH	$Mn^{2+} \rightarrow Mn^{3+}$	
	$Mn^{3+} + H_2O \rightarrow MnO\,OH$	Manganese oxidizers (poorly characterized)
Pyrite FeS_2	$Fe^{2+} + 2S^- \rightarrow FeS_2$	*Desulfovibrio*

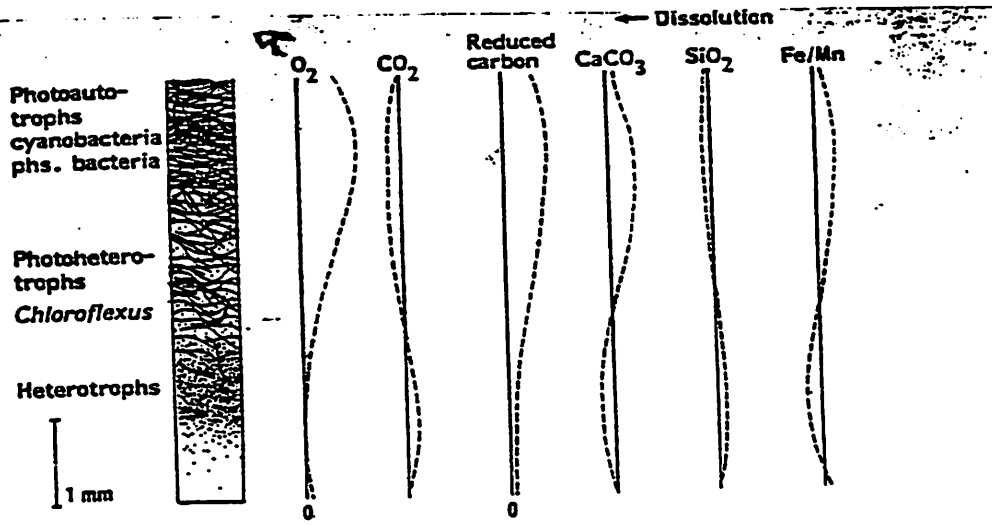

FIG. 1. Schematic illustrating a typical hot-spring microbial mat profile and some of the chemical gradients likely to be present. Relative levels of mineral precipitation and dissolution are shown.

HIGH TEMPERATURE ECOSYSTEMS

TABLE 2 Some net production estimates for flowing thermal and athermal waters.

Location	*Net production* ($gC\,m^{-2}d^{-1}$)	*Temperature* (°C)	*Reference*
Thermal waters			
Octopus Spring, Wyoming	6	50–60	Revsbech & Ward 1984
Ohana-Pecosh Hot Springs, Washington	0.5	39	Stockner 1967 ($CaCO_3$-depositing)
Drakesbad Springs, California	7–12	—	Lenn 1966 quoted in Wiegert & Fraleigh 1972
Mimbres hot spring	0.1	—	Duke 1967 quoted in Wiegert & Fraleigh 1972
Serendipity Springs, Wyoming	4	36–42	Weigert & Fraleigh 1972 (Si-depositing)
Athermal waters			
Waterfall Beck, UK	0.3	8	Pentecost 1991 ($CaCO_3$ depositing)
Itchen River, UK	5	10	Odum 1956 ($CaCO_3$-depositing) (gross production)
Blue River, Oklahoma	20	23–24	Duffer & Dorris 1966 (gross production)
Logan River, Utah	1	8	McConnell & Sigler 1959