Friends of the Pleistocene

Rocky Mountain Section, 44th Annual Reunion

Red Gate to Blue Gate

Lava-Boulder Diamicts and Gravel, Aquarius Plateau through Waterpocket Fold (Capitol Reef), Utah

Glacial? Or debris avalanche & flows?

And: Erosional Geomorphology

Origin of incised meanders
Natural bridge—or is it arch?

Richard B. Waitt U.S. Geological Survey

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Plus: Cosmogenic Ages of Boulder Deposit

David W. Marchetti and Thure E. Cerling University of Utah

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Further: Human Occupation

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FRIENDS OF THE PLEISTOCENE
Rocky Mountain section
September 2000

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RkyMtn FOTP 2000 Stops

DAY 1

1.1 Fish Cr. Cove (archeology–art)
1.2 Overlook from Boulder Mtn alt 8490 ft
1.3 Hickman Pasture last-glacial moraines (hike)
1.4 Moraine-looking debris-av material Boulder Mtn alt 7700 ft *[F&D's CC "drift"]*
1.5 Hwy-12 roadcut in similar material alt 7200 ft *[CC "drift"]*
1.6 Roadcut Hwy 12 at 7080 ft Jct Teasdale Rd. *[CC "drift"]*
1.7 Fremont R. right bank from Fish Cr toward Carcass Cr. (hike) *[CC "drift"]*
1.8 Torrey Rd. at Fremont R near Donkey Cr. confluence (former proposed damsite)
1.9 Terraces Hwy 24, 4 mi E of Torrey along Sand-Sulphur Cr. (short hike)

DAY 2

2.1 Terrace flight betwn Fremont R & Cohab canyon (hike)
2.2 Hickman "Natural Bridge" trail (hike) *[incl. bridge or arch?]*
2.3 Fremont-culture art panels near CRNP Hq
2.4 Big Boulder near water tank; and top of Johnson Mesa: S. of CRNP Hq (hike).
2.5 Grand Wash (drive & hike) *[incised meanders]*
2.6 Capitol Reef Nat'l Park Visitor's Center
2.7 Overlook Goosenecks of Sulphur Cr. 8 mi E of Torrey, 2 mi W of Park Hq

DAY 3

3.1 Terraces right (south) bank of Fremont and overlook South Desert (short hike)
3.2 Oak Cr. Bench (or Notom Bench)
3.3 High terrace above south bank Fremont R. near Pleasant Cr. confluence
3.4 Blue Gate
3.5 Caineville "airport" terrace

Red Gate to Blue Gate

At Red Gate the Fremont River passes from trachyte plateaus to the Great Flexures.
— G.K. Gilbert (*Henry Mtns*) 1877

From 1806 through the 1830s exploring fur tappers in growing numbers threaded their ways through almost all of the western Plains, Rocky Mountains (including northern and SW Utah), and far west. But they avoided the deeply canyoned lands of Colorado Plateau where a horse could scarcely travel. Besides, there were few beaver. Yet in 1826 Ewing Young and Sylvester Patti scrambled up through southeast Utah along the southeast rim of the Colorado's canyons.

Then came the "Great Reconnaissance" seeking wagon routes. In early June 1844 John Charles Frémont crossed 150 miles north of here eastbound from his 2nd expedition. He packed through about same area in early October 1845, outbound on his 3rd expedition. In summer 1853 a Pacific Railroad survey by the Topographical Engineers under Capt. John Gunnison crossed 40 miles north of here. But it was 40-year-old Frémont on his 5th (and last) expedition that came closest to Capitol Reef—a railroad survey competing with Gunnison's but proving an all-weather (winter) route. They left Westport in late September but lost time to a Frémont illness and a spell of danger from Utes. Then a deep cold settled in that froze all but the fastest streams, every crossing treacherous. They ran low of food, but in the unrelenting cold and in a desert with game sparse, they quit hunting. They began eating their horses and mules, and by Green River they were down to few enough they were walking. (Mindful of Frémont's disastrous 1848–49 winter expedition, they agreed not to eat each other.) After Green River they veered southwest from Gunnison's route. Frémont and his party struggled west through here somewhere, probably north of Thousand Lake Mountain, in any case discovering[1] the river that bears his name. It was deep winter when they limped frostbitten, exhausted, and starving through this unforgiving desert wilderness—their geographic records likewise spare.

Geologic exploration of this region began with with John Wesley Powell's Colorado River surveys. From the river they glimpsed the "Unknown" (Henry) Mountains in May 1869 and September 1871. Longtime Mormon explorer "Old" Jacob Hamblin, sometimes collaborator with Powell's 1870–72 Colorado River surveys, explored the Fremont from Rabbit Valley down through the Fold in 1870. Almon H. "Prof" Thompson, Powell's brother-in-law, became field commander and topographer of Powell's second (1871-72) Colorado River survey. In winter 1872 he and a party including Frederick Dellenbaugh and E.O. Beaman triangulated and mapped the topography of a broad region north from Grand Canyon. In June 1872 en route to the mouth

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[1] In the sense David Livingston 'discovered' Zambezi River, Africa, having in 1851 arrived with natives who had floated and fished the river for ages. Western-US explorers—Lewis and Clark, Jedediah Smith, Charles Frémont, John Wesley Powell—anticipated many routes and landmarks from native tales and guides.

of Dirty Devil River to retrieve a stashed boat and resume the river expedition, they climbed Boulder Mountain, crossed the monocline by a creek they called 'Pleasant,' and entered the Henry Mountains over a mesa since called 'Thompson.' Climbing the highest of the Henrys, Thomson named it for his wife Ellen. He retraced his route, rejoined the river party for the run below Lees Ferry, and later from Kanab finished his regional topographic map in early 1873. Meanwhile in 1872 Edwin E. Howell of the competing 'West of the One Hundredth Meridian' survey under G.M. Wheeler traversed the area, climbed Thousand Lake Mountain, and drew several geologic cross sections across the great monocline. From the rather too-military Wheeler survey, Powell in 1873 snatched a chafing Grove Karl Gilbert. And so, in July-August-September 1875 came 32-year-old Gilbert enroute to and from the Henrys. He came through here again in September 1876. When he finished in the Henrys that year, G.K. Gilbert rode out to the north and into history.

> *Toward the north the [Waterpocket] flexure twice divides. One of its branches, the Blue Gate flexure, has a throw in the same direction. . . . The other, the Red Gate flexure, has a throw in the opposite direction. . . .*
>
> — G.K. Gilbert (*Henry Mtns*) 1877, 1880

To early travelers, long rock ridges that thwart travel were 'reefs'—as to a mariner a shoal ridge risky to sail over is a 'reef.' The great monoclinal structure is known as 'Waterpocket Fold.' The great hogback formed in the Glen Canyon Group (Wingate, Kayenta, & Navajo Ss), has also since then been known to travelers as 'Capitol Reef.' Born as a National Monument in 1937, an enlarged Capitol Reef National Park now encompasses most of Waterpocket Fold.

Many of today's names on the landscape originate with the Powell Survey—Waterpocket, Capitol, Henry Mountains, Circle Cliffs. The names 'Red Gate' and 'Blue Gate' appear at the front of G.K. Gilbert's famous 1877 Henry Mountains report—on a photograph of a topographic-relief model made from A.H. Thompson's map. Through these spectacular narrows af Fremont valley each side of Capitol Reef have passed in succession Indian trail, wagon road, and several iterations of Utah highway 24. One comes to Waterpocket Fold today through one or the other of these natural gates.

Since Gilbert's saddle survey, several explorations have divided and mapped the magnificent and colorful layered bedock, some rock units still defined about as Gilbert had them. The most comprehensive map and report of Capitol Reef stemmed from the unranium-exploration period of the 1950s (Smith and others, 1963). Billingsley and others (1987) enlarged and perfected the geologic map.

The only detailed study of surficial geology—in summer 1952 by Richard Foster Flint and Charles S. Denny—focused on glacial geology of the Boulder Mountain area. Geologists from Gilbert on have noted black-gravel terraces downstream, and air-photo mapping got many of them on the geologic maps. But they have remained hardly studied and undated, I was surprised to learn, when serendipitously my field work started in 1992.

The 44th reunion of the Rocky Mountain *Friends of the Pleistocene* will make the newest exploration of surficial deposits spread across Capitol Reef and Waterpocket Fold—Red Gate to Blue Gate—and a little beyond.

Welcome, Friends!

Richard Waitt Sept. 2000

Black Boulders in Fremont River Headwaters

Richard B. Waitt
U.S. Geological Survey

Geography and Concepts

Boulder Mountain and East

Frémont River and tributaries heading on eastmost Aquarius Plateau (Boulder Mountain) and a north outlier (Thousand Lake Mountain [or Flat Top]) cross Waterpocket Fold (fig. 1). The rivers are encanyoned in upturned lower Triassic to upper Cretaceous sandstone and shale—Moenkopi Formation through Mancos Shale (fig. 2). Waterpocket Fold is a monocline whose upended resistant formations erode to a series of spectacular hogback ridges, the largest of them in the Glen Canyon Group (Wingate, Kayenta, and Navajo Sandstones [Lower Jurassic])—"Capitol Reef."

The 'reef'-forming rock belts are thick sandstone beds stratigraphically alternate with thick shale beds that erode to vales. The great Waterpocket monocline and smaller structures east and west with a collective eastward downthrow of 2500–3000 m (8200–9800 ft) expose Permian through Cretaceous strata. The most resistant ridge-forming belts in the west are the Moenkopi Ss (upper Triassic) and the Wingate and Navajo Sandstones (lower Jurrasic) and in the east members of the Morrison Formation (upper Jurrasic) and thick sandstone members of the Mancos and Mesa Verde Formations (Cretaceous) (fig. 2) (Smith and others, 1963; Billingsley and others, 1987). Where Fremont River for 10 km crosses the Grand Canyon Group, its mean grade is steep—175 ft/mi (33 m/km) (fig. 3).

Boulder Mountain and northern outliers of the Aquarius Plateau are capped by Middle Tertiary basaltic-andesite lava overlying weakly consolidated Lower Tertiary mudstone. By a K-Ar age of 24.5 Ma (Best and others, 1980) from just south of Fish Lake (25 mi NNW of Boulder Mtn, 15 mi W of Hen Hole Pk & Geyser Pk), and K-Ar ages of 23.85 and 26.3 Ma at Geyser Peak (Nelson, 1989), the lavas capping Boulder Mtn and northern outliers are late Oligocene in age. These eastmost of these volcanic mesas lie 1300–2600 m above most of Waterpocket Fold ('Capitol Reef') and its valleys.

Large dark-gray (black weathering) boulders mantle benches along Fremont valley and several tributaries that cross Waterpocket Fold. In mainstem Fremont valley they cover Johnson Mesa and scatter down the hillslopes of Fruita. The black boulders at first seem incongruous among the tilted red-and-white belts of sandstone and shale in Waterpocket Fold. But they are identical to dark basaltic andesite that form high cliffs to the west at the edge of Aquarius Plateau

(Boulder Mountain) and northern outliers—Thousand Lake Mountain (Flat Top), Hen Hole Peak, Geyser Peak, and others farther north (fig. 1).

The boulders in terraces along the Fremont and tributaries through Capitol Reef have long been inferred to have been transported by Pleistocene glaciers off Boulder Mountain and by glacial streams draining from them (Dutton, 1890; Gould, 1939; Flint and Denny, 1958). Most of the lava-flow top of Boulder Mountain bears unarguable evidence of glaciation: irregular but locally streamlined erosional topography including closed rockbound debressions; striated and grooved bedrock; boulders delicately perched on bedrock surfaces including high points; diamict bearing striated cobbles. This ice cap flowed east, south, and west off Boulder Mountain as distributary glaciers into streamhead valleys where they built conspicuous drift lobes and moraines.

During reconnaissance fieldwork in 1952, Flint and Denny (1958) studied and mapped the eastside and southside valleys. They inferred a last-glacial Donkey Creek glaciation whose deposits bear only a weak soil (inferred Pinedale age) and a far more extensive and much older "Carcass Creek" glaciation whose deposits bear a distinct calcic soil (inferred Bull Lake age). This work has been generally accepted, for decades having been adopted into, or a the basis of, more recent studies and maps (Smith and others, 1963; Howard, 1970; Billingsley and others, 1987; Repke and others, 1997; Everitt and others, 1997). Of these, the most complete field scrutiny (Smith and others, 1963, p. 46–49) agrees mostly with Flint & Denny's interpretation of "Carcass Creek" deposits. Both geologic maps (Smith and others, 1963; Billingsley and others, 1987) accept most of deposits in Carcass and Fish Creek as Flint & Denny's had them but do not accept F&D's Carcass Creek drift in Pleasant Cr. Both maps also hedge on parts of F&D's outwash phase.

Coarse bouldery debris of landslide and others mass-wasting origins mantle most of the slopes of Boulder Mountain—as Flint & Denny recognized and in places mapped. Yet in the early 1950s the study of debris avalanches and debris flows, and the means to distinguish these deposits from lithologically similar till, were young. Flint and Denny (1958) focused on glacial deposits and mapping drift limits, shunning other coarse deposits. They did distinguish four obvious "tonguelike complex landslides," but they lumped together all other coarse deposits as "boulder deposits of undetermined origin." Flint and Denny explain how they distinguish tonguelike landslides from glacial drift (F&D tables at p. 144 and p. 145), but I find most of the criteria ambiguous, interpretive, and inconsistently applied. Not do they much explain how they distinguish glacial drift from wide areas of lithologically similar "boulder deposits of undetermined origin."

My 1992–1999 (intermittent) study of the area shows the Pinedale drift limits—till-like diamict and small nested moraines—in Fish Creek and Pleasant Creek valleys on Boulder Mountain's east flank not far from Flint and Denny's (1958). These small Pinedale-age glaciers left no recognizable outwash train or terraces downvalley of moraine limits. Flint & Denny's older Carcass Creek "drift" and "moraines" seem to me not glacial at all. Rather they seem to be the hummocky, lobate, leveed landforms and deposits of debris avalanches and debris flows. Viewing and debating the form, sedimentlolgic character—thus the origin, significance, and implications—of Flint & Denny's "Carcass Creek drift" is a theme of this 44th reunion of the Rocky Mountain Friends of the Pleistocene (FOTP). It will be a rocky friends trip.

If this FOTP excursion is to scrutinize some past fieldwork by Richard Foster Flint and Charles S. Denney, Flint has only himself to blame for birthing the Friends. In winter 1934 "Dick" Flint wrote J.Walter Goldthwait to suggest that Goldthwait show his work on glaciolacustrine deposits in Merrimac valley. Seven professors grouped for that meeting. Then a year later Flint writes: "Isn't it about time that the Friends of the Pleistocene meet again?" (R.P. Goldthwait, 1988). Flint not only instigated the first meeting and was its leading participant, but he gave the name to all future meetings. From 1934 to 1975 Flint never missed a Friends (northeast-original) meeting. Charlie Denney—who attended every northeast Friends meeting 1935–1975 and some afterwards—passed away only 13 months ago. The Rocky Mountain chapter of FOTP first met October 1952, a trip Gerry Richmond led to Rocky Mountain National Park. Our September 2000 meeting to Capitol Reef area is the 44th reunion of RkyMtn FOTP.

Glacial till on the one hand, and the deposits of debris avalanche & debris flow on the other, have more characteristics in common than not, and the two are easily and often confounded. On the lower west slope of Mount Ellen, G.K. Gilbert wrote in Sept 1876 *"the valley is occupied by coarse drift that seems morainal."* Then a fortnight later: *"The story of pseudo-moraines at the foot of mountain slopes is here told. The secret is avalanche."* (Hunt and others, 1953, p. 187). In mountains from the Cascades to New England, many others have repeated this excercise: examples of earlier-inferred till and tillite later reinterpreted as a mass-wasting deposit are legion.

Some of the larger landslides off Boulder and Thousand Lakes Mountains apparently fragmented into debris avalanches in the manner of the great debris avalanche(s) off Mount St. Helens in May 1980. The lower ends of these avalanches flowed into the upper reaches of Fremont and Escalante Rivers. Some of the debris avalanches were wet enough to transform into debris flows that slushed 15 km and more down valleys, like wet concrete down a chute. Such dense, fast-moving flows can raft boulders, even huge ones, without rounding them. Some of these flows having overridden and incorporated much river water, transfromed once more—to watery floods that rounded boulders and carried them far down valleys into and beyond Waterpocket Fold. Williams (1984) arrived at very similar conclusions for deposits similar to these shed off the southern edge of Aquarius Plateau toward Escalante (fig. 4).

Coarse bouldery diamict and gravel form widely scattered terracelike surfaces (fig. 5) below which Fremont River and its tributaries have incised 20 to 460 m (mostly >60 m) into bedrock. Similar debris shed from southern Boulder Mountain now forms flat-topped divides hundreds of feet above incised Escalante River headwaters (older deposits) and chokes tributary-canyon heads (younger deposits). Lava-boulder armor resists weathering, thus erosion, far more than bedrock sandstone, which disintegrates grain by grain and is carried away by every rain. The boulder deposits delineate former valley floors but now they are topographically much higher. In places they are high*est*, a wholesale inversion of topography by hundreds of feet since the bouldery flows swept down valley floors.

As a huge stone is sometimes seen to lie
Couched on the bald top of an eminence.
— Wm. Wordsworth (*Resolution & Independence*) 1807

The downstream surficial deposits have remained unstudied except to appear on geologic maps. Smith and others (1963) and Billingley and others (1987) divide them into "pediment gravel", "outwash gravel", and "terrace gravel," but they don't explain the differences and they infer nothing specific about their origins. The field characteristics of most of these deposits are rather similar. Howard (1970) included some of these features on his air-photo-derived map in a study mainly downstream of Blue Gate.

Southern Areas

The present study ranged south to the vicinity of Boulder Town and Escalante River headwaters southeast and south including New Home Bench where Highway 12 rides a linear scrap of black-boulder gravel spectacularly perched 500–550 ft (150–200 m) above Escalante tributaries incised sharply into bedrock either side. We do not visit that area on FOTP, but relations of boulder deposits throughout that area are similar to those of boulders shed off east side of Boulder Mountain. Van Williams mapped and studied a large area west of New Home Bench—south of Aquarius Plateau, east of Straight Cliffs—and much earlier came to similar conclusions about the origin of black-boulder deposits off soughern Aquarius Plateau (Williams, 1984, 1985; Williams and others, 1990; Weir and others, 1990).

Unglaciated North

In contrast to the top of Boulder Mountain, the northern outlier basaltic-andesite mesas—Thousand Lake Mountain, Hen Hole Peak, and Geyser Peak are much smaller, lower, and lack evidence of glaciation. Yet numerous black-boulder deposits east from there are morphologically and lithologically identical to those downslope from Boulder Mountain. The northern deposits cannot be related to former glaciation. Most of these deposits are beyond this FOTP trip, but we visit one west of Capitol Reef and one east. The optional tour (Day 4) north explores the northern deposits.

Inverting Topography

As the Colorado River incises into Grand and Glen Canyons, its tributaries like Fremont and Escalante Rivers also downcut through the sandstone and shale bedrock. These rocks disintegrate grain by grain, tributes carried away by every rain. But basaltic-andesite boulders weather hardly weather at all. They armor floodplains against weathering and thus against erosion. Gradually the river cuts a canyon into rock below the bouldery surface. Over tens to hundreds of thousand years the former river floodplain is left 30, 100, even 200 m above the deepening valley. Eventually this process can leave some black-boulder terraces as the highest elements of the landscape. Thus do valley floors become mesas while divides reduce to valleys.

Age

Geomorphology

During the late Pleistocene the small Boulder Mountain icecap spilled glaciers 2–4 km down the upper reaches of Donkey Creek, Fish Creek, and Pleasant Creek. By the feeble soils on these deposits, they are Pinedale-age. These glacial moraines, though in low vales, remain undisturbed, unburied. Thus even the youngest large landslides and debris flows predate the last ice age: they are older than 14,000 and perhaps 20,000 ^{14}C years.

Boulder deposits downvalley cap mesas commonly 150 to 600 ft (50–200 m) but in places as much as 900 to 1500 ft (300–460 m) above adjacent valley floors. These boulders, carried within one type of gravity-driven flow or another, were initially deposited in what were then the valley floors. But now these deposits are high, some even constituting parts of divides between valleys. Since the boulders accumulated on the floors of Fremont and Escalante Rivers, these streams and all their tributaries have cut down hundreds of feet into bedrock sandstone and shale. At what rate proceeds such erosion—an inch or two a century? Or that in a millennia? The great depths to which streams have eroded down into rock seems to imply that the high coarse deposits are at least several hundred thousand years old, the highest ones perhaps *much* older.

Caliche Rinds

Field-collected data on calcic ('caliche') rinds on the undersides of stones are uncompiled. Thicknesses generally increases from 1 mm on lowest young terraces to several centimeters on high ones. But variablity (standard deviation, or 'noise') on midlevel and high terraces is extreme, and these data may prove hardly useful.

Cosmogenic Isotopes

In a separate section below, David Marchetti and Thure Cerling show that ages they have obtained by ^{3}He method on boulders at various levels range from about 15,000 to 250,000 yrs.

Drainage Systems

Fremont River mainstem

Several large debris avalanches and debris flows shed off Boulder Mountain and surely dammed Fremont River at times. Prominent such fans are in Red Gate north of Teasdale and in mouths of Fish and Carcass Creek.

Bouldery debris flow and floods descended along Fremont River. Several terraces and mesas 100 to 620 feet (30–200 m) above the Fremont valley floor are capped by one or a few meters of coarse black boulders.

Just east of the Park boundary along Fremont River (Utah Highway 24), a conspicuous broad flat terrace nearly 600 feet above Fremont River (fig. 5) is mantled by several feet of river-worn black boulders. The bouldery terrace at first seems a Fremont River deposit, but from boulder lithology seems instead a remnant of the floor of a north tributary, Hartnet Draw. Since the time of these deposits the Hartnet and Fremont have incised 600 feet into bedrock and widened their present valleys.

Pleasant and Oak Creeks

Bouldery flows descended into and along the Fremont's large southern tributaries, Pleasant Creek and Oak Creek (fig. 5). Several terraces and mesas 100 to 400 feet above current valley floors are capped by a few feet of coarse black boulders.

East of the 'reef' the black boulders form flat benches where the floods emerged from the reef's deep, narrow canyons. Driving south along Notom-Bullfrog Road, one encounters them at several erosional levels at the mouth of Pleasant Creek (Notom Bench) and at mouth of Oak Creek. These benches clearly are the ancient floors of Pleasant and Oak Creeks. Since then Fremont River and tributaries like Pleasant and Oak Creeks have excavated canyons 60 m and more into the tilted sandstone of Waterpocket fold.

Deep Creek, Hartnet Draw, and Cathedral Valley

Black bouldery gravel also forms benches high above the northern valleys of the Park (fig. 5), having flowed down from Thousand Lakes Mountain. Cathedral campground (overlooking commonly Deep Creek, the Hartnet, and Cathedral valley) lies atop one of these prominent benches. Just upslope roadcuts expose huge, tilted, deformed landslide blocks, the apparent source of the campground coarse gravel. And from campground bench along Hartnet road, one sees sporadic boulder-capped benches southeast all the way downvalley to Fremont valley. Black boulders cap even the highest mesas along divides to the west (overlooking South Desert) and east. Similar bouldery flows from Thousand Lakes Mountain had descended Deep Creek, where they now lie as benches 60 to 200 m (200–620 ft) above the floor of South Desert.

Escalante River

Landslides have also slumped off the south side of Boulder Mountain and shed huge debris flows into tributaries of Escalante River. Deposits of large debris flows and bouldery floods cap many ridges, a spectacular example lying along Utah highway 18 km southwest of Boulder Town. The highway is balanced on a bladelike sandstone ridge capped by black boulders (New Home Bench), overlooking canyons on both sides cut 150–200 m into white sandstone.

Boulder Town is built on the youngest of the large debris flows off Boulder Mountain. This debris flow descended into and then along present incised canyons, partly filling them but recently enough that streams have cut down through this debris only 15 m. But the upper reaches of Boulder Creek contain last-glacial (Pinedale) glacial moraines, which shows that this debris flow is older than 15,000 years.

An ancient Anasazi village lies on this debris flow just north of Boulder Town. The village, established by about A.D. 1050,[2] shows that this geomorphically young flow is older than 900 years.

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[2] Archeologically dated by pottery remains (Wm. Latady, Curator, Anasazi Museum State Park). Four radiocarbon dates (TX-132 to 135) from charcoal and charred wood from site range AD 835 to 1165 (uncalibrated ^{14}C timescale), each of them with lab error ±80 or 85 yrs (Marwitt and Fry, 1973).

Cosmogenic Dating

David W. Marchetti and Thure E. Cerling
University of Utah

Overview of ^{3}He Cosmogenic Dating

All sub-aerially exposed surfaces are bombarded by high-energy cosmic rays. These rays occur as two types, solar and galactic. Solar cosmic rays are derived from the sun, are composed primarily of protons and have energies in the range of 1–50 MeV. Galactic cosmic rays originate outside in the solar system and have much higher energies (up to 100 GeV). The higher energies of galactic cosmic rays dominate the cosmic ray spectrum reaching the earth, such that the effects due to solar cosmic rays are minimal. As galactic cosmic rays reach the atmosphere they produce a secondary "shower" of particles composed mainly of neutrons (Lal, 1967).

These cosmogenic neutrons cause spallation of atoms into smaller atomic masses. The cosmogenic isotope ^{3}He is created from spallation reactions involving Si and O and other elements. Other significant cosmogenic isotopes created by spallation reactions include ^{10}Be, ^{21}Ne, ^{26}Al, and ^{36}Cl; all of these isotopes are routinely used in cosmogenic dating studies. ^{3}He and ^{21}Ne are stable while the others are radioactive, Once a cosmogenic isotope is produced within a mineral it can either be retained or lost by diffusion or weathering. Certain minerals retain some cosmogenic isotopes while others are lost or masked by the high concentration of the daughter element (e.g., ^{26}Al in feldspar). Thus, ^{3}He is retained by olivine and pyroxene while it is not retained as well by quartz (Cerling. 1990).

Exposed rock surfaces accumulate cosmogenic nuclides through time. The cosmogenic production rate (expressed as: atoms/g/yr) is dependant on the target elements. The production rate at any given location is a function of the altitude and geomagnetic latitude at that location. The production rate for ^{3}He is fairly well known, although the altitude, latitude, and temporal variation corrections are still undergoing slight modifications (Cerling and Craig, 1994a ; Licciardi et al., 1999; Dunai and Wijbrans, 2000). Cosmogenic ^{3}He production rates for the Johnson Mesa terrace in Capitol Reef N.P. ranged from 405 to 426 atoms/g/yr. The production rate for Hickman moraine was 764 atoms/g/yr.

The process of calculating a ^{3}He cosmogenic exposure age is simple in theory but much harder in reality. Samples of the surface to be dated are collected and the desired mineral phase separated and purified. The samples are then analyzed to measure the amount of cosmogenic nuclide present. Once that is known and corrections are made for non-cosmogenic sources of the same nuclide, the production rate is used to calculate the exposure age of the sample. It sounds simple, but there are two major problems, erosion/surface stability and pre-exposure.

The main problem with cosmogenic exposure age dating is rock surface erosion. The earth's atmosphere is a harsh chemical environment for rocks, especially over long timescales. As rock surfaces erode the accumulated dose of cosmogenic nuclides is lost and new rock surfaces are exposed that contain less cosmogenic nuclides than the "true" amount. Eroded samples will give exposure ages that are too young and that are minimum ages. This problem can be partly overcome by using erosion rate models in conjunction with minimum exposure ages. A better solution is to obtain samples that are as unweathered as possible. Sample stability is another problem. Small-sized samples may be disturbed during their history causing them to be turned or moved. This can change the dose of cosmogenic nuclide that the sample surface has accumulated and would also result in a lowered exposure age. Samples should be big enough and the deposit stable enough to ensure that this has not happened.

Pre-exposure is a situation where a sample has a history of cosmogenic exposure before its incorporation into the present deposit. This will give an exposure age older than the true age of the deposit. This can be avoided by sampling deposits that are formed in quick geologic events, such as floods, debris flows, and to some degree glacial deposits. Having a large number of samples is also helpful. One or two older dates in a large population of consistent dates probably indicate pre-exposure.

Sampling Procedures for ^{3}He Exposure Dating

The mineral phases best suited for ^{3}He exposure age dating are olivines and pyroxenes (both cpx and opx). These two phases have been shown to quantitatively retain cosmogenic 3He over timescales of interest for Quaternary geologists (~ < 1Ma) (Cerling and Craig, 1994b).

The black boulder deposits in the Capitol Reef area are derived from lava flows outcropping on the summits of Boulder and Thousand Lakes Mountains. The petrology of these flows has been described as porphyritic andesite (Smith et al., 1963) or as a basaltic-andesite (Mattox, 1991). They contain abundant phenocrysts of plagioclase (~20–30%) and clinopyroxene (3–6+%), so they are well suited for ^{3}He exposure age dating. One problem with the rocks is their nucleogenic age. Using the K-Ar method, Mattox, (1991) determined an age of ~23–25±1.5 Ma for a basaltic andesite flow from the top of Boulder Mountain. Older igneous rocks can pose difficulties for ^{3}He exposure age dating due to ingrowth of ^{3}He from ^{6}Li (n,α) ^{3}He reactions and excessive ^{4}He from the decay of Uranium. In this study, these problems were addressed by collecting shielded samples to determine the non-cosmogenic components of ^{3}He and to correct for nucleogenic ^{4}He.

Sample collection is perhaps the most important step in cosmogenic exposure age dating. Sample surfaces must be as unweathered as possible (often called primary surfaces), preferably with less than 1 cm of erosion since depostion. Samples that appear to have moved, spalled, chipped, or appear weathered should be avoided. Primary surfaces are often polished (water lain deposits), striated (glacial deposits), and in desert environments will often have desert varnish and wind polish. Another commonly dated surface is desert pavement. Desert pavements have been shown to accurately date the time of emplacement of surfaces on which they have formed because they are inflationary in origin (Wells et al., 1995).

Samples are generally taken from the crown of boulders using a hammer and chisel; desert pavements are simply picked up. The uppermost 4cm's of the sample is the desired portion, be sure to get enough sample to obtain ~2 grams of pure mineral separate. Sample locations should be checked for potential sheilding problems. Topographic features that block the skyline at angles greater that 20 degrees up from the horizon should be noted. The degree of sheiding up from the horizon should be recorded as well as the degrees of rotation (out of 360°) that the feature blocks the sample. These values are used to calculate the samples total sheilding which is then used, along with the samples altitude and latitude, to determine the production rate for each sample. When sampling desert pavements the soil stratigraphy should be checked for a prominent Av (vesicular A) horizion. This will help insure a true desert pavement origin.

After field collection samples are cut or broken to obtain only the upper 4 centimeters. The samples are then washed, crushed, and sieved in preparation for mineral seperation. Usually the 20–40 or 40–60 mesh seperates are analyzed. Mineral separation can be done many ways but typically involves: (1) removal of strongly magnetic grains with a covered hand held magnet run through the sample, (2) magnetic separation using a Franz or Carpco separator, and (3) further separation and purification using heavy liquids.

Once a pure mineral separate is obtained it is placed in 10% HNO_3 to remove any organic or carbonate material that might be coating the grains. Next the sample is etched with 5% HF in a sonicator for 5–30 minutes to remove any matrix or other silicate material possibly coating the grains. The samples should then be visualy inspected and hand picked to remove any foreign material. After this step the samples should be ready for crushing and analysis.

^{3}He and ^{4}He concentrations were measured at the University of Utah Noble Gas Laboratory on a MAP-251 noble gas mass spectrometer. Gas was released using a modified Turner furnace heated to >1400 °C. Reactive gases were removed by SAES getters; Ar and Ne were separated from He cryogenically. The detection limit for ^{3}He in this system is about 50,000 atoms.

Ages Obtained

Our results are discussed in detail at Field Stops 1.2, 1.3, 2.1, and 2.4. Briefly here: Hickman moraine samples date between about 15 and 23 ka, dating Pinedale glaciation there. Johnson Mesa boulders date between about 170 and 210 ka while desert-pavement dates in same area are discordantly mostly between 110 and 125 ka. Dates from boulders of the approximately highest terrace above Cohab Canyon show the surface to be older than 160 ka, surely a distant minimum-limiting age. The Anthill deposit high on the south flank of Thousand Lake Mountain dates to 250 ka, certainly a distant-minimum age for that deposit.

Erosional Geomorphology

Richard Waitt

Incised Meanders

Whereas streams flowing in sand and gravel in arid regions typically form low-sinuosity frequently shifting braids, many streams flowing in muddy alluvium—typical of in humid regions—form long looping meanders, some growing back on themselves to intersect and cut off. From the air such floodplains show loopy meanders cutting across scrolls of many older abandoned ones. Many streams of the Colorado Plateau have cut deep hard gorges that meander like looping humid-region floodplain streams. Popular is an idea that these meanders originally form on a muddy floodplain, then uplift causes the streams to cut down into underlying rock. Thus while incising hundreds of feet into layered sedimentary rocks, former floodplain meanders are imagined to survive scarcely altered. The map shape of a looping gorge is taken as evidence of a floodplain-meander birth. Evidence of the seminal floodplain disappears except the meanders themselves (fig. 6). This theme is much reiterated in some textbooks and especially in popular works featuring the Colorado Plateau (Chamberlin and MacClintock, 1927; Stokes, 1969, p. 43–44; 1987, p. 194–195; Chronic, 1990, p. 65, 279, 289, 293).

Earlier literature, then geomorphology textbooks, distinguished two classes of incised meanders—entrenched and ingrown—by shape of the valley walls at the ends of meander loops (Davis, 1906; Rich, 1914; Moore, 1926; Cole, 1930; Mahard, 1942; Thornbury, 1954, p. 142–144; Easterbrook, 1969, p. 193). If the profiles of the left and right bank are symmetrically steep, a meander must have incised vertically into rock and is called an *entrenched* meander. But the profiles of many incised streams at meander bends has the outer (concave) bank notably steeper than the inner bank. A bend having this pattern—evidence that the meander grew while it incised—is called an *ingrown* meander. Moore (1926) argued that many incised meanders of the Colorado Plateau are ingrown.

Where Fremont River and nearly all tributaries including Grand gorge and Capitol gorge are cut through the resistant Wingate, Kayenta, & Navajo Sandstones and resistant parts of the Morrison Fm, the gorge cross-profiles at meander bends are almost invariably asymmetric: outsides of bends are steep to vertical to overhanging but insides of bends slope 50° and less. In plan view, meanders drawn between the cliff tops are less sinuous than those now on canyon floor. These relations—increasing sinuosity with erosional depth—show that the meanders have enlarged while they incised. The companionj process of meander straightening is evident in incised-meander cutoffs that can be seen in the topography along most incised streams. Thus it seems that in many reaches incised meanders in Waterpocket Fold developed as they incised. There is no evidence of inheritance from a former floodplain. A similar inference has been made of incised meanders farther east (Moore, 1926; Hunt and others, 1953, p. 173).

Natural Bridges and Arches

By the rude bridge that arched the flood,
Their flag to April's breeze unfurled,
— Ralph Waldo Emerson (*Concord Hymn*) 1837

Natural bridges and arches are among the most visited and intriguing of landforms in the Colorado Plateau. Both form in rock terrain being actively incised. In Emerson's couplet 'bridge' and 'arch' are nearly synonymous. But for natural stone spans the terms are differentiated by how a span is thought to have formed. The genesis of most arches and bridges can be inferred from their morphology and rock structure.

An *arch* forms by gravitational collapse of the rock beneath—a process often away from streams and more or less independant of any stream. An arch typically spans no stream, though a streamlet from upslope may use any newly low course. Many arches originate in erosionally resistant, wide-jointed rock that becomes narrowed into a standing a rib by deep vertical erosion along parallel joints (Cruikshank and Aydin, 1994). They concentrate at Arches National Park, a prolifically jointed area in resistant sandstone near a deeply incised Colorado River tributary.

A *natural bridge* forms by a stream that, having once flowed around or over an area, is diverted by some natural process such as ingrown meanders intersecting to flow under this area. Natural bridges typically span the stream that excavated the rock and effected the small-area stream capture. The specific origin of most true bridges is apparent from topography. In Natural Bridges National Monument the abandoned incised loopy meanders that grew and eventually intersected to form Sipapu and Kachina natural bridges show clearly in the landscape (fig. 7).

Hickman "Natural Bridge"

Only 3 miles from Fruita in a tributary of Frémont canyon in Capitol Reef National Park, Hickman "Natural Bridge" lay undiscovered until 1940—two thirds of a century after geographic exploration and settlement began. The Hickman span is formed in the Kayenta Sandstone, in a succession of thick (1–3 m) beds of massive medium sandstone each bed grading up to a thin (10–30 cm) of fine sandstone, siltstone, or shale—a succession of graded-bed couplets.

Hickman span overlooks an unnamed creek, dry except during rain, incised sharply 120 ft below and just east of Hickman's base. On the upslope side of the span an inconsequential incised 'wash' is also dry except during couldburst. It heads only 400 feet back, is narrow and without tributaries, only an etched-out joint zone. Along this joint-slot are no rounded stream-worn boulders or cobbles, though angular talus clasts of hard sandstone litter the sides and head of the gully where they fell. Even at peak flow it is too weak to move stones of any size. All it can do is remove sand that weathers grain by grain from the cliffy sandstone walls and talus boulders. Only this feeble drainage passes beneath the Hickman span.

The Hickman span seems to have formed by collapse of shaley beds exposed near the base of both abutments. Such collapse became possible when the incising eastside wash and the simultaneous etching of the westside joint both cut below a shale layer, removing former lateral support. Caving from both sides of this narrow standing rock rib eventually eats through. Hickman makes no genetic sense as a natural bridge. But its origin as an *arch* is understandable.

Analogs

A one-sided 'blind' arch (or alcove arch, or niche arch) forms in the near-vertical sides of canyons cut in massive, coherent rock where the canyon is cut deep enough to expose shale or other mechanically weak beds beneath the coherent rock. Many examples indent the Wingate Sandstone where its base with Chinle Shale is exposed on steep valley sides. West of Hickman bridge on the north wall of Fremont valley are at several, some of them large. Other picturesque examples along this Wingate/Chinle contact lie Long Canyon 29 mi south of Frémont canyon. A large, deep arch alcove at this horizon lies along Utah Hwy 95 in North Wash 8 miles above Colorado River (fig. 8) (Hunt and others, 1953, fig. 88).

These blind arches form when the easy erosion of the underlying shale beds undermines the overlying sandstone, which therefore also collapses in one area while remaining supported on both side. The result: an archlike niche. A full, open arch cannot form without a corresponding canyon behind it.

Blind arches of this sort are common throughout the canyoned sandstone of the Colorado Plateau, numerous examples for instance marking the walls of Zion Canyon. The illustrations of J.W. Powell's popular 1895 book on Colorado River explorations showed in Grand Canyon scores of deep alcove niches working up into the Redwall limestone from collapsing strata below.

Human Occupation of the Capitol Reef Area

Lee Kreutzer and Adrienne Anderson
National Park Service

The culture history of the Capitol Reef area stretches back at least 11,000 years, from PaleoIndian to historic times. Evidence of PaleoIndian occupation is sparse but intriguing, consisting mostly of a few lanceolate (Clovis and slightly later styles) projectile points found on the ground surface.

Archeological evidence left by Archaic peoples (9,000 BC to AD 600) is more abundant, especially at higher elevations, where ancient fire hearths, scattered dart points, and occasional Archaic-style petroglyphs and pictographs can be found. The most dominant Archaic rock art has been designated the Barrier Canyon Style and fetes life sized, trapazodial anthropomorphs with richly decorated torsos that lack appendages (fig. 9). Many of the figures have large, staring eyes and have been referred to as "ghost figures." The anthropomorphs often are surrounded by small animals, including a reoccurring dog, and other small elements. While direct dating of rock art is problematic, evidence suggests Barrier Canyon style was popular between 2,000 BC to AD 1.

Capitol Reef is best known, however, for the material culture of the Fremont people, contemporaries of the better-known Anasazis. It was here, along the Fremont River, in 1928 that archeologist Nöel Morss first noted differences between the archeological sites of the Fremont River and the well-documented Anasazi sites of the Southwest. Instead of pueblos, kivas, fine black-on-white pottery, and woven sandals, he found rock shelter occupations, pit houses, plain gray or black ceramics, and distinctive leather moccasins. Based on these and other diagnostic traits, Morss defined "Fremont Culture" as separate and distinct from Anasazi culture.

Fremont culture is dated archeologically from roughly AD 600 to around AD 1275. Despite the differences identified by Morss, Fremont and Anasazi cultures do appear to have had much in common. Fremont culture overlaps temporally, and to some extent geographically, with the Anasazi occupation of the area. The two peoples both cultivated beans, squash, and maize, resided in similar environments, and used the same styles of projectile points. Consultants from modern Indian tribes (e.g., Hopi and Zuni, among others) descended from Anasazi people tell us that the cultures archeologists have identified as Anasazi and Fremont were, in fact, the same people with different adaptations and stylistic preferences.

Differences in stylistic preferences are most visibly obvious in the rock art of the two cultures. Fremont-style rock art is most notable for its anthropomorphs—bucket-headed, trapezoidal humanoid-shapes that dominate numerous panels in the area (fig. 10). Tribal consultants have told us that these figures represent katchinas, and that they are depicted at sites where religious ceremonies were held long ago. They also identify clan symbols, migration stories, planting calendars, and other meaningful messages among the area's petroglyphs and pictographs.

At roughly the same time that Fremont material culture disappears from the archeological record, new styles of arrowheads and pottery, traceable to Ute and Paiute ancestors, appear. These new occupants do not rely on cultivated plants, but choose instead a hunting and gathering lifestyle. Archeological sites attributable to these groups are typically open-area camps, with lithic scatters, fire hearths, and other surface features. Ute and Paiute people, as well as Navajos, continued living in the Capitol Reef area until their lands were claimed by settlers. Evidence of their contact with Europeans and Euro-Americans is sometimes found in rare petroglyphs depicting horses, domestic cattle, or trains (fig. 11).

Field excursions will include at least two archeological sites, including rock art panels, created by these early inhabitants of the Waterpocket Fold.

Road Log, Day 1

Day 1 General route: Torrey to Teasdale to Boulder Mtn at Fish Creek to Torrey to west part of Capitol Reef National Park.

MILES

0.0	Start in Torrey on Hwy 24 westbound at Café Diablo—about ½ mi west of Torrey center and 1½ mile west of intersection ot UT Hwys 24 and 12.
1.0	Fremont River.
2.3	Topographic axis of broad black-boulder fan. Shed from Boulder Mtn, it packed Fremont R. against north side of valley, where it maintains sharp cliff in Moenkopi Fm.[3] Cliff above the Moenkopi is Shinarump Ss-congl. (upper Triassic), the lenticular, discontinuous basal member of Chinle Fm. Narrows of Fremont valley west of here G.K. Gilbert called 'Red Gate.' Turn left (south) and ascend fan towards Teasdale.
3.4	Roadcut in high part of boulder fan. To SW fan heads in tributaries wending through bedrock.
3.7	Enter Teasdale.
4.1	Far side Teasdale. Pointed landforms on right next few miles are very steep faulted monocline that flattens abruptly west. Thus across this structure Najavo Ss dropped to level of Moenkopi on east.
5.5	Tall ridge ahead "Cocks Comb" is Najavo Ss caught in this monocline. Near-horizontal bedding in Najavo just west and in Moenkopi not far east. Next few miles across fan from Boulder Mtn carrying black boulders as large as 3–4 m.
9.6	Fish Creek.

We take private track to archeologic site in Fish Creek Cove (*this mileage omitted from in log*).

STOP 1.1. Archeological site *(Lee Kreutzer and Adrienne Anderson)* (fig. 1).

This site serves as an introduction to area prehistory with evidence of both Archaic and Fremont cultures. It is typical of the large rock shelters that provided protection from the elements for prehistoric occupants of the area and served as a canvas for recording scenes, ceremonies, "deities," daily activities, stories, and events. There are few remaining structures at

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[3] Abbreviations: this informal fieldguide is full of them. Most should be self evident. Here are some of them: Fm = Formation; Mbr = Member; Ss = sandstone; Ls = limestone; ID = intermediate diameter (of measured boulders); plag. = plagioclase; xl = crystal; ***P, Ŧ, J***, and ***K*** = symbols for Permian, Triassic, Jurassic, & Cretaceous; Hwy = highway; ka = 1000 yrs (old); Ma = million yrs (old); ***Jw/Ŧc*** = contact Wingate over Chinle.

this site, first documented by Nöel Morss in 1931, but both Barrier Canyon style and Southern San Rafael Fremont style rock art panels occur.

Resume mileage count from before turnoff to Stop 1.1

MILES

9.7 Here and for next ⅓ mi are a series of roadcuts through morainelike topography and coarse-bouldery matrix-poor diamict. Flint and Denny (1958, their locality 4) here described a calcic soil developed on "till of Carcass Creek drift." Large boulders hear measure between 1.5 and 2.0 m in intermediate diameter (ID). Most are angular to very angular and are *clast*-supported rather than matrix-supported—some of them imbricated. A mile east we shall later examine a similar cut of this material and see whether we think it either "till" or "drift."

10.7 Intersection with UT 12 from Torrey. Turn right.

10.9 Turn right onto USFS Road 179 toward Blind Lake. Road ascends black-boulder fan. Bedrock knoll ahead also capped by black-boulder gravel.

11.5 Left at "Y" in road, ascending main track.

11.7 Roadcut in bouldery gravel with deep calcic soil. Large boulder measures 2.5 m.

12+ Succession of 3 roadcuts show angular diamict. White patches seem to be clasts of the Flagstaff Fm. (Paleocene-Eocene) that underlies the lava cap of Boulder Mtn. Such fragile clasts make sense in debris-avalanche & debris-flow deposits, but not in glacial till.

12.7 Dixie Nat'l Forest.

13.3+ Area cleared of Pinon-Juniper cover. Ridge to east and roadcut ahead at switchback resemble glacial moraine and till. *But* . . . . (this will be Stop 1.4.)

15.9 Highest and third of three N-pointing (left-turning) switchbacks.

STOP 1.2. Oveview of many of Day-1 stops (fig. 1).

Explorers, travelers, and painters of the 19th centuries outdid each other seeking the gloomy, chaotic "sublime" over the merely pastoral. In the American West they included explorers John Muir, Clarence King, and John Wesley Powell, and landscape painters such as Albert Bierstadt, Thomas Moran, Gilbert Munger, and William Keith. Capt. Clarence E. Dutton, geologist and aritst on loan to the Powell Survey, found his atop the southeast point of Boulder Mountain:

> *It is a sublime panorama, The heart of the inner Plateau Country is spread out before us in a bird's-eye view. It is a maze of cliffs and terraces lined off with stratification, of crumbling buttes, red and white domes, rock platforms gashed with profound cañons, burning plains barren even of sage—all glowing with bright color and flooded with blazing sunlight. Everything visible tells of ruin and decay. It is the extreme desolation, the blanket solitude, a superlative desert.*
>
> — Clarence Dutton (*High Plateaus Utah*) 1880

The view north from here (Stop 1.2) features Thousand Lake Mountain. High on its north flank protrudes Ant Hill, mantled by black boulders derived from Th Lk Mtn. The Ant Hill boulder deposit now perches 1500 ft (460 m) above adjacent drainages excavated into rock.

East view is down to Carcass and Fish Creek choked by large bouldery fans shed from Boulder Mtn down into Fremont River; in distance on Waterpocket Fold are the upturned edges of Wingate and Navajo Ss, like sharks' teeth.

To southeast prominent knoll Lion Mountain is capped by black large-boulder gravel from Boulder Mtn and now stranded 400–1000 ft (125–300 m) above adjacent vales excavated in Carmel and Navajo Fms.

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Cosmogenic Dating *(Marchetti & Cerling)*:

The Anthill, a conical peak 2835 m in altitude, is capped by a black boulder deposit derived from lava flows outcropping on the top of Thousand Lakes Mountain 6 km north. The crown of the Anthill is littered with boulders ranging from pebble size to 2+ m in diameter. The deposit is meters thick and is eroded along its margins, spilling boulders onto the slopes below. It lacks desert pavements.

Boulders on the Anthill are extremely weathered. Most are lichen or moss covered, heavily pitted, and show evidence of recent spall or surface breakage. The ground around boulders is littered with fragments from them. It is unlikely that primary boulder surfaces remain. Samples from the Anthill were heavily weathered. Only the least weathered surfaces were taken, and from boulders big enough not to have been moved by tree fall.

The boulders analyzed give a wide range of cosmogenic exposure ages, evidence of severe erosion of the boulder surfaces and the deposit. The oldest age indicates that the Anthill surface is older than 250 ka. Considering the decrepit state of the deposit, this is a minimum date, the deposit probably much older.

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16.5 Glacial debris and small moraines (last glacial) all through here.

16.8 Great Western Trail. Turn left toward toward Fish Creek ("Parking Area").

16.9 Turn right into parking area (an old well-drilling platform). *Please don't try to drive up road above here.*

STOP 1.3. Walk up road about a mile to Hickman Pasture. The valley meadows are bordered both sides by high, sharp, weak-soiled, seemingly last-glacial lateral moraines. We climb to crest of north (left-lateral) moraine.

The lateral moraines bounding Hickman Pasture are 400 m apart where they depend from a shallow U-shaped valley; they widen to 650 m before arcing into an end-moraine loop only a mile (1.5 km) from the canyon mouth. The terminal morainal debris can be followed down to altitude 8640 ft surely, to 8500 ft probably, and tongues of it to 8200 ft perhaps. Both lateral moraines are as high as 120 ft (37 m), have side slopes typically 22–32°, and sharp, narrow, bouldery crests. Basaltic-andesite boulders are angular, many as large as 2 m in intermediate diameter (ID), a few as large as 3.2 m, one 4.2 m ID. Only rarely do stones show striae, and those poor, though many have small areas of polish. There is little of no caliche undercoating. At one moraine-crest site weathering rinds measured on 10 pebble-cobble-sized stones average 1.2 mm. All this suggests a last-glacial (Pinedale) age for this glaciation.

The basaltic-andesite rocks have 20–35% plagioclase phenocrysts, including 'megacrysts' as large as 1 x 2 cm.

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Cosmogenic Dating *(Marchetti & Cerling)*:

The Hickman moraines were deposited by an outlet glacier emanating from the ice cap that existed on Boulder Mountain. Cosmogenic samples were taken from the largest boulders on the crest of the ridge. We looked for boulders that showed little to no signs of weathering. Three samples were taken from Hickman moraine at various locations along the ridge. The preliminary ^{3}He cosmogenic ages are given below and shown in figure 1.

Sample No.	Age (yrs B.P.)
Hick-BD-01	16,100±1,600
Hick-BD-02	19,000±1,900
Hick-BD-03	20,900±2,100

The three ages indicate deposition coincident with the Pinedale glaciation in the Wind River Range which has been dated at 16–23ka (Phillips et al., 1997; Gosse et al., 1995b).

****

17.0 Leave parking area. Retrace route down.
20.6 Roadcut at switchback and area downslope where Piñon & Juniper trees have been cleared by chaining.

***STOPS 1.4 through 1.7**: This series of four stops progressing farther downslope scrutinizes deposits that Flint and Denny (1958) examined, described, and interpreted as "Carcass Creek drift" (glacial till, moraines, outwash) of inferred Bull Lake age. Smith and others (1963, p. 46–49) accept, reiterate, and elaborate Flint & Denny's interpretation of "Carcass Creek" deposits. (Bull Lake is considered to equate to marine Isotope Stage 6, ca. 130,000–160,000 yrs old [e.g., Imbrie and others, 1984]).*

STOP 1.4. Ridge visible to east and the roadcut material may at first look like glacial moraine and till—as Flint & Denny (1958) took these deposits and landforms to be (fig. 12). So did I during first half of fieldwork.

> *The ice was here, the ice was there,*
> *The ice was all around:*
> *It cracked and growled, and roared and howled,*
> *Like noises in a swound!*
>
> — Samuel Taylor Coleridge (*Ancient Mariner*) 1798

But look closely at the form of 'moraines.' A pair of ridges resembles lateral moraines, but at the widest they are spaced only ½ mi (800 m) apart. Then followed upslope only ¾, the lateral ridges all but *merge*, the two spaced only 500 ft (150 m) apart. The broader left-lateral ridge downslope actually consists of two smaller sharp ridges 400 ft (60 m) apart.

Substop A. Roadcut has many clasts smaller and more rounded (subangular to subround) than farther downslope; they are in places matrix-supported, some clasts perhaps snub-nozed 'glacial' shapes, some maybe with vague striae. Caliche undercoat rinds only 0–1.5 mm. Walk down to where chaining operation got ridgecrest.

Nonsubstop B. Flat surface NW of 'moraines: contains boulders to # m with caliche undercoatings to at least 3 mm.

Substop C. Outer left-lateral morainelike ridge has black boulders to 1–1.5 m ID but many smaller subangular to subround. Little or no caliche rinds.

Substop D. Inner or two left-lateral morainelike ridges is 400 ft from the outer. Boulders to 2 m ID. Side slopes to 17–25°. Walk back up this ridge to Substop F.

Nonsubstop E. Boulders on flattish surface outside (east of) right-lateral ridge. Angular boulders to 2.2–2.5 m, rarely to 5.0 m ID. All stones are angular to subangular. Caliche undercoating to at least 1.5 mm. Ribbed by several irregular NE-trending (flow-parallel) ridges.

Substop F. Ridge abruptly ends on a promontory. It overlooks not only the vale west between these 2 small left-lateral ridges but also overlooks south into a far deeper sharply *transvese* vale, bounded by its own morainelike sharp ridges. This transverse vale crosses not only the inner of the 2 left-lateral ridges, but cuts across the right-lateral ridge as well—which is here merging upslope with the left-lateral ridges. This arrangement is impossible of moraines.

Vertical airphotos acquired in 1997 clarified the story (fig. 13). Topographically this is a perfect example of a distributary breakout of a debris flow across one of its levees. In fact, this whole cluster of ridges is thus perfect: why the right-lateral morainelike ridge system diverges from the left lateral ridge system just upslope from here; why ¾ mi downslope from here this left-lateral ridge system again breaches transversely across and truncates the inner ridge; why below several of these leveed breakout breaches the spreading debris looks vaguely like a pahoehoe lava surface of numerous convex-downslope nested ridges enclosing closed depressions. But this is fragmental rock, not lava. In geomorphic detail they resemble lumpy debris-avalanche and leveed debris-flow deposits on the flanks of some stratovolcanoes (e.g., Waitt and Begét, 1996, 2001?) If there is geniuine glacial debris in these ridges, the debris avalanche and flow(s) must have included glacial moraines.

Return to vehicles. Proceed downslope.

22.9 Hwy 12. Turn right and proceed southeast upslope.
23.2+ Over next ¾ mi series of long roadcuts both sides expose diamicts full of *very* angular boulders and cobbles despite having come 7 mi from Boulder Mtn source scarp.
24.6 Road left to Grover. Continue on 12.
24.9 We have passed completely off the bouldery diamict onto Moenkopi Ss. This *Ŧm* dips southwest, off Miners Mtn anticline. Diamict boundary is sharp: not one black stone through here. One sharp terminus of Stop 1.4 feature is the steep lobe 600 yds southwest.
25.2 Cross onto sharp terminus of another black-boulder diamict lobe.
25.25 Another road left. Turn onto it and park on wide shoulders. Ahead on Hwy 12 roadcut on west side is Stop 1.5. *No parking, please on Hwy 12 shoulder.* ***Beware of fast uphill traffic around 'blind' bend at roadcut!***

STOP 1.5. Roadcut on Hwy 12.

Errors, like straws, upon the surface flow;
He who would search for pearls must dive below.
— John Dryden (*All For Love*) 1678

Steep roadcut several meters high exposes monolithologic diamict of angular to very angular gray basaltic andesite as large as 1.2 m ID but mostly ≤0.75 m. Most are clast supported or are in a stoney "matix" of very angular clasts of identical rock type. Exposure shows fragile clasts—deformed claystone pods of Flagstaff Fm. One measure 2.5 x 3 m, another 4 x 1 m.

Flint & Denny mapped this with their "*Carcass Creek drift with morainic topography*". The surface includes numerous vaguely arcuate east-west ridges, convex downslope (north); these ridges enclose many closed depressions. F&D only *called* this topography "*morainic*," giving no critical description that would distinguish from other genetic possibilities. The extreme angularity of the clasts in the roadcut, the general lack of a matrix (except of crushed very angular stones), and the large fragile clasts all seem improbable as till. There are no striated stones here, no snub-nosed pentagonal "glacial"shapes, nor other characteristics *diagnostically* of glacial till. These textures and the topography are more typical of debris-avalanche deposits.

On airphotos, surface detail of large area east of Hwy here looks like large pahoehoe lava flow—about 10 nested gently arcuate ridges with average spacing 260 ft (80 m). This flowlike lobe issues upslope from between a pair of levee-like ridges (enough of the term 'morainelike') spaced about 0.4 mi (600 m) apart. This whole complex ridge-and-lobe feature lies outside right margin of the Stop 1.4 ridge-and-lobe complex west of here. But morphologically the two are indeed similar.

This flowage had enough momentum to cross a broad low area just south of here and then run up 65 ft (20 m) onto the Moenkopi high just to north, where its outer margin is *very* sharp. A frictionless object purely under its own momentum (not being shoved from behind) would be flowing 20 m/s (44 mi/hr) to achieve this runup.

25.3 Turn around and retreat downslope northwest on Hwy 12.
28.1 Across from Boulder Mtn road, turn right and park along old gravel highway.

STOP 1.6. Roadcut and bouldery ridge E side of Hwy 12 opposite junction Teasdale Road. Flint and Denny (1958) described this area—including the roadcut and ridged terrain ¾ mi west (at Stop 1.1 turnoff)—as quintessential "Carcass Creek drift." Thus (p. 122):

> *The distal half of the FishCreek–Grover drift lobe consists of Carcass Creek drift. It is composed chiefly of* ***till*** *with morainal topography. Many exposures of till are seen in cuts along the roads that traverse the lobe; elsewhere the presence of till is* ***inferred from the ubiquitous end-moraine topography*** *and from great numbers of surficial boulders of all sizes.*
>
> *Carcass Creek drift commonly has a subparallel series of* ***looped, boulder-covered end moraines consisting of long laterals curving into incomplete, nested terminals.*** *The laterals approximate 50 feet in height in their upstream segments and gradually become lower in the downstream direction, curving into terminal ridges no more than 10 or 15 feet high. Successive morainal ridges are separated by narrow swales floored with sandy alluvium and colluvium.* [emphasis added]

Substop A. Atop low round ridge, basaltic-andesite boulders here are of megacrystic variety (>15% plag, xls large as 2 cm). Many boulders in 1–1.5 m ID, several 2.5 to 3.5 m ID—in size acceptable for till, but there's a lot of them. But they are angular, none with faceted, pentagonal "glacial" shapes, none striated. Over large areas stones are all one rock type and color, with little of no sandy matrix. Upslope 1–2 mi WSW of here Navajo Ss (***Jn***) crops out both sides of a gap. It seems improbable that a glacier through there would not bring many ***Jn*** clasts here. A debris avalanche or debris flow down this same path would glide by, eroding little ***Jn***.

Roadcut shows black-boulder deposit is only 3 m thick: beneath this 3 m of vaguely horizontally bedded soft, brown sandstone and siltstone, apparently *in-situ* much-weathered Moenkopi Fm.

Substop B. But trouble: 300 yds west is a flat boulder just south of Teasdale Road. Its upper surface measuring 2 x 1 m is etched by flutes and grooves parallel to long axis of boulder, looking very much *glacial*. Why is *this* here?

28.1 Intersection of Hwy 12 and Teasdale Road. Turn right on Hwy 12, downslope north.
29.1 We've emerged onto a flattish fill that slopes generally 2° north but interrupted by a large step sloping 6° north. F&D mapped this as "Carcass Creek outwash."

Ten large boulders that litter this surface along next half mile measure 0.8 to 1.5 m ID (mean 1.36 m). Most are angular to very angular, no visible rounding. This is "outwash"?

30.1 Fremont River. Park in large area well off shoulder.

STOP 1.7. Deposits shed from Boulder Mountain spilled two tongues into Fremont canyon, via Fish Creek and via Carcass Creek. We hike east about 1½ mile above south bank of Fremont R. We start on a lobe of debris shed down Fish Creek that fanned and turned clockwise downvalley into the Fremont and jammed the river to its north side. We end on a far larger lobe shed down Carcass Creek that spread and turned counterclockwise *up* the Fremont and also pinned the river to its north side.

Substop A. Lowermost Fish Creek. Flint and Denny (1958, Plate 6) inferred deposits in the ravine of lowermost Fish Creek and adjacent Fremont River as "Carcass Creek till," and the flat terracelike surface just east as "Carcass Creek outwash." Roadcut and south bank of Fremont River shows gravelly sand of local sandstone frags and round-stone pebble gravel, the ubiquitous black surface boulders a veneer only 3 m thick. Here 9 miles from source, basaltic-andesite boulders are angular to subangular, only a few subround, none round, the largest 1.1–1.7 m ID, all of megacrystic variety. Smith and others (1963, Fig. 18) show a cut on the old road ⅓ mi to SW exposing *6 m of very angular* boulder diamict.

The flat "outwash" surface east of Fish Creek gully shows little difference: boulders are subangular and 1.1–1.3 m ID. Caliche undercoatings are 1–5 mm commonly but 10–20 mm locally.

Substop B. Lower half of gully walls expose coarse black-bouldery diamict. Being matrix supported, and the matrix itself being poorly sorted and nonbedded, the diamict superficially resembles glacial till. The black clasts range pebbles through boulders 2.8 m ID. Most are very angular to angular, some subangular, a few subround. None seem snub-nosed "glacial" shapes, none striated. This suite of textural characteristics more suggests deposition by catastrophic debris flow than as glacial till.

The bouldery, matrix-rich diamict is at least 5 m thick. It is overlain by about 4 m of sand, that capped by about 1 m of sorted pebble gravel. The sand is silty very-fine sand (median grainsize 3–3.5 φ) with delicate, fine laminae 1–5 mm thick, evidently lacustrine. From this stratigraphy it appears that the diamict dammed Fremont River, and for long enough that 4 m of sand accumulated at this downstream end of a lake. Capping gravel is of local flaggy Ss, a later fan built from south valley side.

Substop C. Across on north wall of Fremont valley, base of reddish Moenkopi Ss overlies thin-bedded Kaibab Ls (limestone & calcareous siltstone [Permian]), as Fremont R. begins it's canyon crossing of Miners Mtn anticline. Plastered over this bedrock is the black-boulder diamict, its upper limit sharp and horizontal. This line shows that the diamict down Fish Creek merged with the larger lobe of it down Carcass Creek. Neither of them sloped much up or down this reach of Fremont valley.

Flight of strath terraces on this (south) side of the Fremont suggests that the lake dammed by the Carcass Creek diamict lobe failed gradually, in stages.

Substop D. Flint & Denny show this west end of the diamict lobe choking the mouth of Carcass Creek as "Carcass Creek drift"—till overlapped by outwash. But though we are 10 miles from bedrock source, the large black boulders are almost all very angular to angular, only a few subangular. Most of them are 0.5–1.5 m ID, but there many are 2–3 m and a few 3–4 m ID. Just west (in creek gully) deposit has matrix of small but very angular black stones—as at Substop B. South part of surface buried 2+ m deep in fan of sandstone flags from cliffs to south.

Just downstream Fremont is not only pinned to north valley side but Kaibab bedrock crops out low on south side as well. Thus Fremont here is in bedrock canyon. The Fremont's natural valley must lie 1000 ft (300 m) south, buried by the diamict fan.

30.1 Turn around and return to Hwy 12, heading *south, up* Hwy 12.
30.7 Fish Creek Rd. Turn right on it. Head south toward Teasdale.
32.2 Junction Teasdale Rd. Turn right (west) toward Teasdale.
34.3. Junction road right toward Fremont R. and Torrey (Donkey Creek). Turn right (north) toward Torrey.
35.1 Irrigation canal overlooking channel of Fremont R.

STOP 1.8. (Ben Everitt) Abandoned Garkane hydropower station and penstock is to the west. The narrows to the south flanked by bedrock Moenkopi (*Ŧm*) was studied for potential damsite in 1987. Pleistocene valley here lies buried beneath gravel south of modern Holocene valley here (fig. 14).

35.1 Continue north across Fremont R.
36.9 Jct. Hwy 24 at Torrey. Turn right (east) on 24.
37.7 Jct. Hwy 12. Continue east of Hwy 24.
39.3 Wide overlook area on right. Pull into it.

STOP 1.9. Substop A. Overlook "Gilbert" terraces.

A succession of about 9 pediment-like terraces, planed-off Moenkopi Fm capped by black-boulder gravel variously 6 to 116 m (20 to 380 ft) above present level of adjacent Sulphur-Sand Creek. Terraces slope to S, SSE, and SE generally parallel to present Sulphur Creek, the high terrace sloping 45 ft/mi (27 m/km). Lava boulders are clearly more resistant to erosion than bedrock Moenkopi sandstone & shale.

39.3 Return to Hwy 24, continue east.
39.7 Sand Cr. (mislabeled 'Sulphur Cr.').
40.4 Cross Sulphur Creek (unlabeled). Today it carries mostly local sand.
40.9 Gravel-sorting area on right. Pull into it and park. **Stop 1.9B**

STOP 1.9. From parking platform, climb to high terrace.

Substop B. On the upstream (north) corner of high terrace, contact of gravel over Moenkopi sandstone. Many large boulders, but deposit is mostly pebble-cobble gravel. Imbrication of pebbles near base suggests S-ward flow—consistent with slope of terrace and indicating source from Thousand Lake Mtn (to NW) rather than Boulder Mtn (to W). Gravel is 5.5 m thick, but two internal fine-sand layers suggest it comprises 3 separate layers (average 1.8 m thick).

Largest basaltic-andesite boulders on top of high terrace measure 1.3 to 1.6 m ID, same as many float boulders downslope. Whereas boulders on Boulder Mtn's east flank (Donkey, Fish, Carcass, Pleasant, & Oak Creeks) are conspicuously porphyritic (20–40%) and megacrystic (1–2 cm plag. xls), boulders on these terraces are more sparse in plagioclase phenocrysts (5–15%) and the largest of them are 1 cm and less. This seems to be a systematic field characteristic of rocks shed from basaltic-andestie lavas capping Thousand Lake Mtn and more northern peaks.

Besides the black-lava boulders, the deposit contains a few percent of round pebbles of resistate clasts—chalcedony, siltstone, chert—apparently derived from weak Flagstaff Formation (Paleocene-Eocene) that underlies the capping lava (Oligocene) of Thousand Lake Mtn.

Gilbert (1880, p. 120–127) was probably the first to describe surfaces at the base of mountains that look like alluvial fans but are cut in nonresistant rock (mainly shale) and are either bare or only thinly veneered with rock waste (fig. 15). He called them 'slopes of planation.' During an ensuing discussions 1890s–1950s in the literature (e.g., Bryan, 1922; Blackwelder, 1931; Rich, 1935) these surfaces came to be called 'pediments.' Gilbert's description was concerned mainly with places on the lower slopes of the Henry Mountains, but his best example of numerous such levels was in the Fremont valley (Gilbert, 1880, p. 125–126):

> *. . . a few miles [below Red Gate] . . . abandoned flood-plains form a series of . . . benches. Each one is carved from the rock in situ, but each is covered by a layer the rounded river gravel.*

He used this to build his argument that most river terraces are not fills from the bottom up but are cut in rock from the top down as the river gradually incises.

The main quibble I have is that it seems that the bouldery gravel here, as all over this area, is not ordinary "rounded river gravel" that Gilbert's argument implies but requires a catastrophic mass-wastage event off the flanks of Boulder Mtn or Thousand Lakes Mtn to deliver the basaltic gravel is such large quantities.

On his three trips through here to and from the Henrys, Gilbert was almost entirely concerned with bedrock stratigraphy and structure. In his field notes he mentions the 'trachyte' rubble in several places but has little time to devote to it. Just above where Pleasant Creek enters the reef he notes on Sept. 8, 1876 (Hunt, 1988, p. 121):

> *The benches at the gap bear trachyte from Aquarius Plat. I count four of which highest is 100 ft above water. The stream bears trachyte only in its bed. The flood plain is built entirely of sand.*

Thus: in the past (the terraces) Pleasant Creek carried coarse boulders; now its floor is mainly of local Ss.

Prelude to tomorrow: on cliff of Meeks Mesa, large blind arch in Wingate (*Jw*) working up from weak Chinle (*Ћc*) beds at cliff's base.

End Day 1.

Road Log, Day 2

No one but a geologist will ever profitably seek out the Henry Mountains. I will mark out a route which will give him the best introduction to this wonderful land. Through the Red Gate he enters the land of cañons. He does not follow the valley of the Fremont far. Where the river enters a cañon he bears to the left, and by the aid of trail which the Indians have made finds a sinuous but easy pathway along a monoclinal valley, following the outcrop of the lower Shinarump. At his right sandstone rises to form the plateau through with the river defiles. At his left the Vermillion Sandstone stands in a vertical wall. Beneath his feet are the shaley sandstones of the Shinarump Group, bare of vegetation and displaying a profusion of ripple marks, such as is rarely if ever equalled. A ride of twelve miles brings him once more to the Fremont River, which emerging from its cañon dives at once into a still deeper cañon through the Vermillion and Gray Cliff Sandstones.

— G.K. Gilbert (*Henry Mtns*) 1880

Day 2 General route: Torrey to Capitol Reef National Park: Fremont R., Cohab Canyon and Hickman trails, Fruita area, Scenic Drive and Grand Wash. *Four stops (2.1, 2.2, 2.4, 2.5) have limited parking. Tight car-pooling today is necessary—perhaps even some ferrying.*

MILES

0.0	Start: UT Hwy 24 eastbound at intersection UT Hwy 12 in Torrey—the modern short-cut version of Gilbert's "bear to the left."
2.7	Sulphur Cr.
3.1	Parking area for terraces of Stop 1.9.
3.25	On cliff of Meeks Mesa, large blind arch in Wingate (*Jw*) working up from weak Chinle (*Ŧc*) beds at cliff's base. The variegated Chinle is what forms Painted Desert in northern Arizona.
3.3	Enter Capitol Reef National Park.
4.0	Road parallels E-W up-to-south fault. Basaltic dike intruded fault plane, exposed intermittently on left for next ½ mile.
4.9	Twin Rocks eroded in Shinarump Ss and conglom., the discontinuous, lenticular basal member of the upper Triassic Chinle Fm (*Ŧc*). Shinrump is more resistant than underlying brown Moenkopi, and far more resistant than overlying reddish Chinle shale. Next ¼ mi tilt in Moenkopi beds related to the fault.
6.5	In big reëntrant and erosional gap to NE, the up-to-south fault brings Moenkopi-Shinarump horizon up against Chinle.
7.0	Chimney Rock. *Ŧs*/*Ŧm*.
7.5	Turnoff right to Goosenecks of Sulphur Cr. (will be Stop 2.7).
7.6	Begin long descent of obliquely down dip of Moenkopi beds off Miner's Mtn anticline and into east-dipping Waterpocket Fold (monocline).

9.7 Above: picturesque contact Wingate SS over Chinle Fm. dips east on WP monocline.
9.9 Turnoff to CapReef VC
10.0 Capitol Reef N.P. Visitor's Center. With Gilbert, we have come "once more [almost] to Fremont River."

Staging area. Stops 1.1 & 1.2 both start from a small but popular parking Nat'l Park lot, and FOTP must minimize our occupancy of it. Please cram into few vehicles & leave others here. Drive is short (May even have to ferry some folk from here.)

10.0 Rejoin Hwy 24 east. Wingate Sandstone (Powell survey incl. Gilbert called it "Vermillion Cliffs") is eolian whose forset beds dip generally ESE. Gilbert measured one foreset layer 105 ft thick.
10.7 Historic Fruita school.
11.0 Petroglyph panals. This will be Stop 2.3.
11.4 Chinle/Wingate contact dives undergournd east, on WP monocline.
11.8 Hickman parking lot (left). Park but leave room for others.

STOP 2.1. (fig. 1). Cross Hwy 24 to Cohab Canyon trail. We shall ascent a flight of 12 rock-cut terraces capped by black boulders, from about 100 to 475 ft above Fremont River. River level here is 5360 ft (1635 m). We start up along trail but ascend higher terraces off trail.

Substop A. Lower benches. Mostly basaltic andesite of megacrystic variety. Boulders subangular to subround as large as 1.0–1.8 m ID.

Substop B. Subangular megacrystic huge boulder >4.6 m ID (axis partly buried). Can water alone roll such a boulder? For how far? Or does its presence demand debris flow reached this far downcanyon? Boulder perhaps has rolled from next small terrace higher.

This next higher terrace at altitude 5500 ft (~1680 m), 140 ft (43 m) above Fremont R., has several large subangular black boulders: largest 2.6 m, others 1.5–2.0 m ID. In this flight of terraces, this general horizon has all the very large boulders. There's a similar coarse horizon at this level on north valley side (toward Stop 2.2). Yet most smaller stones at this level are subangular to subround, some even round, seemingly water-rolled. Maybe a thin debris flow over mostly waterlaid gravel, as at Fruita watertank?

Substop C. Next many terraces higher are similar to each other. Boulder-gravel caps carry stones of abraded (rounded to subangular) shapes, largest ones variously 0.7–1.8 m ID. Most are megacrystic variety but a few not. Thus the large boulders seem concentrated at one horizon, 140 ft above the Fremont.

Substop D. Overlook.

Come on, sir; here's the place. Stand still, How fearful
And dizzy 'tis to cast one's eyes so low!

— Shakespeare (*King Lear*) 1605

On these two high-level boulder deposits, terraces are rather degraded, largest clasts are 0.7 to 1.05 m ID, most but not all megacrystic. Cut on north and west edge shows deposit 2–3 m thick over ***Jk*** sandstone. Most boulders subround to rounded and clast supported, little matrix—surely waterlaid. Thus except for horizon down at Substop B, we seem below Fruita to be beyond range of bouldery debris flows. By this far downvalley almost all debris flows had transformed to bouldery flowflows.

High*est* black-boulder deposit (at altitude 5835 ft (1780 m), or 475 ft (145 m) above Fremont R.), is 1.65 m thick over ***Jk***. Its boulders are subangular to subround and only to 50–75 cm ID. Caliche undercoat plates are as thick as 12 mm—hardly news, since some stones on much lower (and younger) surfaces—Johnson Mesa, Carcass Creek—wear much thicker undercoats.

Terrace profiles. Johnson Mesa, sloping downvalley from altitude 5837 to 5680 ft (1780–1732 m), seems to grade downvalley to prominent terrace remnant on north side Fremont here at 5500 ft (1677 m), and then to terrace remnant at 5440 ft (1660 m) farther downvalley. Thus high*est* black-boulder surface here, 475 ft (145 m) above the modern Fremont, is also 335 ft (102 m) above Johnson Mesa gradelevel.

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Cosmogenic Dates *(Dave Marchetti and Thure Cerling)*

Samples from the uppermost Cohab Canyon terrace are nightmarish in terms of cosmogenic dating. They are on a relatively small terrace, the clasts are small and could have been reworked, the deposit is severely eroded, and the top of the deposit presently is almost certainly not the original depositional top. There is some desert pavement but is poorly developed. This is a bad surface to date cosmogenically because it may not be the original surface of deposit and does not contain primary surfaces. We dated it anyway, to try to acquire some useful information from this high deposit. But results lived up to our expectations. The ages calculated for this surface only suggest that it is older than 160 ka. This is not terribly helpful since stratigraphic position indicates that it is significantly older than the Johnson Mesa surface dated at ~190ka (fig. 2).

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Bedrock: Moenkopi Ss up through Navajo Ss. Fremont canyon to NW exposes the Permian.

> *He watched his enemy [GOLIATH] go down, falling free the first three hundred feet past the Kayenta caprock, glancing off a protruding ledge below. Excellent Newtonian mechanics, Hayduke reflected, still good enough for regular fucking government work. GOLIATH falling, falling. The dragline cleared the base of the Wingate cliff, struck the Chinle slopes a thousand feet below and bounced rolled skated to the lip of the Moenkopi wall and another free-fall. It sank down and down into the deep time of geologic history—from Jurassic into late Triassic, from late Triassic into early Triassic, ricochetting off the Cutler Formation, shattering itself finally upon the unyielding monolithic fine-grained rock of the Cedar Mesa Sandstone deep in the Permian Age.*
>
> — Edward Abbey 1990

STOP 2.2. Hickman 'Bridge' trail. From trailhead at parking lot, come up through bedded Kayenta Ss bedrock capped here & there by black-boulder deposits 1–3 m thick of round to subangular clasts typically ⅓–¾ m ID, the largest 1.2–1.5 m ID. Most but not all boulders are megacrystic—from Boulder Mtn.

Substop A. Here we have climbed up to a terrace 1½–2 m thick over ***Jk*** where size suddenly is large: several subangular black boulders in 2.0–2.3 m ID range. Trailside exposure suggests martix support in pale-brown silt-sand, but exposure is poor. This is about same level as terrace of large boulders on opposite side valley (Stop 2.1, Substop B): altitude 5500 ft (~1680 m), or 140 ft (43 m) above Fremont R. This doesn't necessarily prove but lends support to hypothesis that large black-boulders there, including the 5-m job, came in one unusual debris flow, which also touched this site.

Next higher terrace two terraces 1⅔–3⅓ m thick are of round to subangular clasts of maximum size 0.9–1.1 m ID—like terraces below Substop A. Thus as on south valley side, the horizon of larger and less-rounded black boulders seems unique in an flight of terraces otherwise seemingly clast-supported *fluvial* gravel. Some former terraces are reduced to relics: isolated boulders perched on bedrock.

Substop B. Hickman 'Natural Bridge'. Discovered only in 1940, the Hickman span formed within a long, narrow blade of rock standing between the two deeply etched NNW-trending joints just east and west of the blade. Both abutments are in shaley beds erosionally weaker than the massive arch-supporting sandstone. To the east (downstream) is a deeply incised tributary from the north. Upstream and parallel to this is an etched-out joint system, a near-vertical slot 25 m deep and only 10–15 m wide. Its floor bears no water-worn stones, not even small ones.

When erosional level got down to and just below the conspicuous 1–1½-m-thick red-shale bed, weathering started to undermine and collapse the overlying thicker & harder sandstone. It is like formation of the 'blind' arch at Wingate/Chinle contact on the edge of Meeks Mesa near Twin Rocks (near Stop 1.9). The process here worked back into the rock rib from *both* incised joints, but probably mostly from the deeper exposure east. When the last of the narrowing eardrum-like shale septum falls out, an adolescent arch is born. Then over time it enlarges to present form.

The Hickman 'bridge' spans an inconsequential drainage that flows only rarely, during occasional heavy rain, flow too feeble to carry more than sand weathered from the bedrock walls. It was inessential to the structure's formation.

The Hickman span seems genetically an *arch*, not a natural bridge.

Nonsubstop C (above Hichman span). Highest black-boulder gravel on this side is about 5980 ft (1824 m), some 145 ft (44 m) higher than highest on opposide side at Stop 2.1D

Substop D. (*Binocular view east of Capitol Dome*). About ¾ mile east of here Capitol Dome is the central uneroded core of the cutoff of a large incised-meander loop at altitude about 5900 ft, or 620 ft (190 m) above modern Fremont River. The cutoff would have shortened the 1.2 miles around the loop to a tenth that. The Fremont River gradient through here being more than

60 ft/mi (18 m/km), just before cutoff the river would have been 60 ft or so higher on the upstream side of the narrow septum than on the downstream side—a gradient of 500 ft/mi or more, a hydraulic gradient to encourage and effect a cutoff. A permeable bed at that level, dipping steeply downstream dip on the monocline would encourage groundwater flow through it, promoting sapping up from the downstream side. Capture likely would have left a spectacular, long, natural bridge spanning the Fremont similar in form to but much larger than modern Sipapu bridge at Natural Bridges Nat'l.Monument.

On the outside (north) of the cut-off meander is a patch of black-boulder gravel with clasts to about ¾ m diameter at altitude 5900–5920 ft., which is about right to match gradient from the highest gravel at 5980 ft just upstream of Hickman arch (near Nonsubstop C). Thus the processes that have from time to time shed coarse-boulder gravel down the Fremont have operated similarly during at least the last 600 ft of the river's incision through rock.

11.9 Return to Hwy 24 west, back up toward V.C.
12.5 Lot on right for petroglyph panels. Park here.

STOP 2.3. Archeologic Site *(Lee Kreutzer and Adrienne Anderson)*

The extensive rock art site interpreted here is generally thought to be the "type site" for the Southern San Rafael Fremont style rock art. The figures and scenes depicted were first described by Julian Steward in 1929 and later by Morss (1931). They actually extend, intermittently, along the Wingate face eastward for a quarter of a mile (fig. 16).

12.6 Return to Hwy 24 west.
13.6 Turn left toward Scenic Drive. Leave stowed cars at VC, as next stop (2.4) also has parking limits.
13.8 Brimhall House in trees left.
14.1 Small dirt road right. Some vehicles park here; overflow at Blacksmith's shop ⅓ mi ahead on right, or beyond that on road shoulder along orchard.

STOP 2.4. Climb road switchbacks up to vicinity of buried watertank.

Substop A. Above highest switchback near water tank.

A. Bedrock: Two unusual features visible just to northwest:.

1. Moenkopi Fm contains huge boulders of conglomerate of mostly autochthonous flat-pebble Moenkopi clasts but also 2% of exotic rounded pebble & cobble resistates (sandstone, chert) derived perhaps from Precambrian source. These are like the resistates in Flagstaff Fm. that end up in black-boulder deposits.

2. Disconformity atop Moenkopi overlain by buff-colored friable vaguely plane-bedded sandstone now collapsing along vertical joints. Fine Ss interrupted by granule-gravel beds. Seems T or early Q—emplaced after Moenkopi's tilted on WP Fold and later beveled off before being capped by gravel that now forms terrace.

B. "Terraces".

1. High terrace gravel a little higher than here and ½ mi due west, midway between canyon mouths of Fremont R. and Sulphur Creek, is all of *local*-bedrock clasts—limestone and Ss clasts, *no* black boulders. Slopes to N, therefore probably deposit of Fremont R. flowing at this level at time it did *not* carry black boulders. But then, maybe it's a Sulphur Cr deposit.

2. Johnson Mesa deposits. (Flint and Denny mapped all this as CarcassCreek-age glacial outwash.)

High roadcut behind watertank. ***First,*** base of bulldozer cut exposes about 2 m of bedded soft sand and sandy pebble gravel with a few imbedded boulders (*Interpretation: normal Fremont R. deposit, much as today*).

Second, that overlain abruptly by 4 m of round-stone clast-supported black-boulder gravel, mostly pebble-coble gravel but with largest clasts 60, 80, & 95 cm ID. Imbrication of gravel clasts and foresets in sand lenses ind flow toward NE, N, and even NNW and NW! (*Interpretation: powerful water-flood flow down the Fremont whose left side is expanding counterclockwise across valley floor toward Sulphur Cr, almost perpendicular to main valley trend*).

Third, (farther east in ascending cut) that gravel in turn overlain abruptly by coarse diamict with angular-subangular black boulders as large as 1–2.5 m ID, partly matrix-supported and with interstices mud-filled (*Interpretation: catastrophic debris flow*).

3. Huge boulder. Imbedded in this upper diamict is a megacrystic basaltic-andesite (Boulder Mtn) gigantic boulder, measuring 12.3 x >6 x 4.1 m (40 x >20 x 13 ft). Can water alone transport such a clast? How can thus stuff be "outwash"?

Exposure beneath the boulder is revealing of emplacement process. The huge boulder 'floats' in a matrix comprizing angular to very angular pebbles & cobbles themselves in a muddy matrix full of granule-sized angular basalt clasts. Can this conceivably be outwash? Till? It is a rather typical texture of a castrophic landslide-runout debris flow off a volcano.

Nonsubstop C. Near Johnson Mesa "terrace" apex ½ mi to SW:

On south side Fremont R., terrace remnants 80–120 ft higher than top of Johnson Mesa surface similarly have black boulders as large as 1 m. Downvalley gradient of this surface would project 200–220 ft below the grade of highest boulder surface above Cohab canyon (Stop 2.1D).

Near apex of J-Mesa fan-terrace: subangular black boulders to 1.7–2.3 m ID, caliche undercoats 10–15 mm thick. Down-fan a little, the surface has form of broad whalebacked bars a few mtrs high, many 10s of mtrs long, streamlined parallel to terrace slope, studded with many subangular boulders in 1.5–2.0 m range, a few to 2.5 m (*suggests catastrophic-flood deposit*). But on NW side of these bars is flatter surface a few mtrs lower of mainly subround-rounded black boulders, none larger that about 90 cm ID (*indicates streamlaid deposit*). So here's another indication of catastrophic debris-flow flood spreading over floodplain fan of Fremont-R. boulders

Substop D. Climb above roadcut to N. edge of Johnson Mesa. Surface litterred with subangular black boulders of megacrystic variety, rarely as large as 2.5 m ID.

Bouldery deposits like this one ranging far downstream from Flint & Denny's inferred "glacial" margins vary from a few to 15 m thick. They contain angular clasts commonly 1–3 m, rarely ≥6 m in diameter—huge stones "floating" in a diamict of smaller angular clasts with massive sandy-mud matrix. Stream-rolled boulders ordinarily become rounded downvalley, but in Fremont drainages many boulders far downvalley from glacial limits are angular.

This site shows that some coarse diamicts of angluar clasts overlie clast-supported gravel of subrounded cobbles and boulders that are clearly streamlaid. The diamict flow therefore swept down along an existing valley floor whose stream (at least in flood) had carried round-clast boulder-cobble basaltic gravel. The coarse diamicts extend as far as 32 km from bedrock source and 28 km from limits of last-glacial (Pinedale) deposits that are but little incised. A classic glacial-outwash explanation seems dubious for these downvalley deposits. Because the deposits are so coarse and linear (they lie within present valleys or form divides between them), are of diverse and inconsistent heights, and are locally thick, they are also poor candidates for remnant pediments of planation (or of interrupted downcutting). The deposits must have initiated as enormous landslides whose wet toes slushed down valleys as huge bouldery debris flows.

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Cosmogenic Dates *(Marchetti & Cerling)*

The black boulder deposit capping Johnson Mesa is the largest and most continuous deposit sampled for cosmogenic dating. The deposit is 1.5 km long, 0.6 km wide, 10–15 m thick and, ~90 m above the present flood plain of the Fremont River (fig. 17 shows relation between Johnson Mesa profile and Fremont River profile).

We sampled desert pavements and boulder surfaces for ^{3}He cosmogenic dating. The boulder surfaces selected were as unweathered as possible and were from boulders large enough not to have been moved by tree-fall or creep. We inspected the boulder surfaces looking for a smooth surface polish (most likely from wind) and no evidence of surface spallation. There were few good boulder samples from the deposit as a whole but the three we obtained were excellent. We also sampled six desert pavements. Desert pavements have been shown to faithfully record the cosmogenic age of the surface on which they form (Wells et al. 1995). The desert pavement samples were obtained by finding a well-formed desert pavement on a flat surface, checking the soil below the gravel armor for a vesicular A horizon, and then collecting enough basaltic-andesite clasts to make a sample (~1.5 Kg of rock). Both the boulder and desert pavement samples were collected at various locations along the length of the deposit. We found no relationship between the age of the sample and its location along the deposit (table, and fig. 18).

Sample No.	Age (yrs B.P.)
Boulders	
JM-BD-01	189,400 ±18,900
JM-BD-03	191,300 ±19,100
JM-BD-04	180,500 ±18,100
Desert Pavements	
Fruit-DP-01	112,700 ±11,300
JM-DP-01	116,000 ±11,600
JM-DP-02	123,000 ±12,300
JM-DP-03	115,500 ±11,600
JM-DP-05	158,000 ±15,800
JM-DP-06	117,800 ±11,800
JM-DP-07	146,400 ±14,600

The cosmogenic dates from Johnson Mesa are interesting in three respects. First, there is a significant offset between the boulder and desert pavement ages. This offset ranges from ~70 ka for five of the samples and ~40 ka for two of the samples. Apparently, some factor (climatic?, fluvial?) was hampering desert pavement formation for some period of time. Second, the boulder age of ~190 ka is the emplacement age of the deposit and is not related to a major Rocky Mountain glacial event as previous researchers have thought (fig. 18) (Flint and Denny, 1958). Finally, five of the desert pavement ages give very consistent dates between ~110–125 ka. These ages are within the range of Bull Lake glaciation and a possible connection between the two is suggested. Perhaps the deposit itself is not related to glaciation, but its abandonment as a terrace related to glaciation.

Using the calculated exposure age of ~190 ka and a bedrock thickness of ~80 m, (90 m [terrace tread to river] – 10 m [deposit thickness]), an average bedrock incision rate of ~40 cm/ka is estimated for this stretch of the Fremont River.

****

14.1 Return to pavement, continue south.
14.45 Blacksmith's shop.
14.65 Fremont R.
14.7 Gifford Farm House.
14.8 CRNPark campground.
15.2 Start Scenic Drive. Road is in Moenkopi Fm dipping E on Waterpocked Fold.
16.0 Summit. Succession *Jw/Ŧc/Ŧm*. No Shinarump (base of *Ŧc*) cliff-former yet.
16.7 Shinarump (*Ŧs*) begins to wedge in, thicken south.
17.0 Road to Grand Wash. Turn down it. *Ŧs* now 2 m thick.
17.2 Oyler Mine. Uranium mined 1904–1920s. Additive to water bottled to "cure" rheumatism & other ailments.

17.5 On N. wall ahead a blind arch maybe 150 ft high in Wingate Sandstone (*Jw*), grown up from base in weak shaley Chinle Fm (*Ŧc*). Niche requires strong supporting rock—Wingate massive and but sparsely jointed. Just west where ***Jw*** is closely vertically jointed—no arch.

17.8 On north side another blind arch in the Wingate that worked up from partings in lower in the sandstone. On south tributary wall still another blind arch entirely within Wingate. Cassidy "arch" is partly visible from here to west, developed in bedded fluviatile Kayenta Sandstone (***Jk***) above the more massive eolian Wingate. By inferrable genesis (seeming to require at least groundwater passing downdip east to sap out weak beds from below), Cassidy 'arch' seems to me genetically more nearly a natural bridge—though a hybrid.

18.1 Several smaller blind arches in this stretch. Rockfall boulders to 7 m.

18.2 End of road. Park where you can.

STOP 2.5. Hike downcanyon. No basalt boulders in Grand Wash, only local sandstone clasts.

Hike will take us from Kayenta Ss into overlying Navajo Ss. Interesting contrasts between them. Kayenta has variable grainsize, graded beds, foreset beds only a few decimeters tall, soft-sediment folds, and others characteristics of fluvial deposition. Foreset dip west (± a few compass points), Jurassic steamflow thus that way. Navajo Ss is uniform medium sand arranged in sweeping foresets 2–10 m tall, characteristics of eolian deposition. Navajo foresets dip generally ESE but range widely toward NE, E, SE, and S. If continent lay in the tropics during the Jurassic, these are trade-wind (southwest) directions, since rotated counterclockwise many compass points.

Substop A. Gently walled area on left side (northwest) before first meander bend is a cutoff incised meander whose floor is 120 ft above present floor of Grand Wash. Thus meanders can straighten themselves during incision of Grand Wash into Kayenta Ss.

Just beyond a sharp bend right in valley is a bend left. The ends of both bends are asymmetric, the outer walls nearly vertical, inner ones a stepped slope. Path of river drawn through this topography 150 ft higher than present wash is far less sinuous than present wash. These meanders have clearly grown in length and sinuosity as they have incised. They are of *ingrown*, not *entrenched*, type. So what of the common argument that such loopy meanders originated on a floodplain far overhead—long-vanished?

Supstop B. Upon entering the massive Navajo Sandstone, gorge narrows to 35 ft (10 m). First two incised-meander bends in tight gorge are less than 100 years apart along a track of low sinuousity. The cross-profiles of each is asymmetric: outside-bend wall vertical to overhanging while inside bend is 65°–75° toward stream (fig. 19). Thus these incised meanders in the Navajo are also of ingrown type. Use the gorge-top topography to draw in the wash at erosional 400 ft higher, and stream is straight. Sinuosity has developed during incision. Does one need to invoke a former muddy floodplain—a different climate and gentler topography—to explain these meanders? Do ingrown-type meanders anywhere tell anything about former climate, floodplains, or slopes?

After FOTP an interesting drive & hike is Capitol Wash 4½ mi farther south on Scenic Drive. No basalt crossed Miner's Mtn into that route either (but Capitol carries bits of basalt from road gravel). Capitol Wash was a trail, wagon road, and Utah "highway" 24 from 1870s until present Hwy 24 was completed in 1962 along the Fremont.

Turn around and backtrack to:

22.7 On left, Nat'l Park Visitor's Center.

STOP 2.6. Capitol Reef National Park Visitor's Center. Large plaster-relief map of Capitol reef area. Books, maps, cards, etc. for sale.

22.8 Intersection UT Hwy 24. Turn left (west).
25.2 Turnoff left to overlook. Take it.
25.2 Loop end or road.

STOP 2.7. Short walk to canyon edge. Goosenecks of Sulphur Creek.

Rock of canyon bottom to east is Cutler Group (Permian) including Cedar Mesa Sandstone. It is overlain by 400 ft (cliffs) of Kaibab limestone (upper ***P***), that by 400 ft (gentler cliffs & slopes) of Moenkopi Ss (upper ***Ŧ***).

Interpretive sign shows popular notion: looping meanders initiate on low-gradient floodplain and then survive scarcely changed through many hundreds of feet of incision into bedrock. The cross-profiles at meander ends here are far more symmetrical than is typical of Grand Wash, yet steeper outside of some meander bends show that even these are at least partly of the ingrown type. Meanders enlarged at least some during incision through ***Ŧm*** and ***Pk***. *How much had they developed at higher levels while stream cut through Glen Canyon Group?*

To ENE several small blind arches and incipient ones (archlike cracks) developed in poorly jointed part of Wingate.

To NW, black-boulders shed E from Thousand Lake Mtn cover high erosional surfaces on ***Ŧm*** to ***Jn***.

End Day 2.

Road Log, Day 3

Here is your true Ozymandias. Look on my works, Ye Mighty, and Despair! Your destiny, as man, is to be a fossiliferous stratum in the crust of the earth; the land where Time is everything and nothing makes it plain. Many layers of history are already gone, in places more than a vertical mile of them gone. They survive clear to the Eocene in the Plateaus because lava capped those tablelands and retarded the eraser. Shellac over a mark on a blackboard and you can preserve it for a while, but not forever. Geology knows no such word as forever.

— Wallace Stegner 1942

Day 3 General route: Capitol Reef Nat'l Park Visitor's Center down Fremont, up Pleasant Cr. and follow Entrada Ss strike valley to Oak Creek (or only to Notom Bench?), then down the Fremont to beyond Blue Gate. Today from Torrey we completely cross the great Mesozoic section exposed in Waterpocket Fold—lower Triassic (Moenkopi Fm) through upper Cretaceous (Mancos Shale). The rocks appear conformable, but there are minor inconspicuous unconformities—in places between the Entrada and Summerville, between the Summerville and Morrison, and especially at top of the Morrison (upper ***J***)—which is overlain directly by Mancos Shale (upper ***K***), even the Dakota Ss (lower & upper ***K***) hogback missing.

MILES

0.0 Intersection UT Hwy 24 at turnoff to Capitol Reef Nat'l Park Visitor's Center, 10 miles east of Torrey. Head west down Hwy 24.
1.9 Hickman trail parking.
3.4 In May 1997 a great slab fell from cliff in Navajo sandstone (***Jn***) onto Hwy 24. Many examples of open-cracked, vulnerable sandstone overlook the valley and highway.
3.8 Ahead on skyline left layered Carmel Fm (***Jc***) overlies east-dipping Navajo.
4.5 Grand Wash (of Stop 2.5) enters from right.
6.0 Historic cabin.
6.7 Next 0.4 mi. cross manmade cutoff of Fremont R. incised meander (still in Jn).
7.1 East-dipping thin-bedded Carmel Fm. (mudstone, siltstone, sandstone, limestone) has now come down to highway.
7.5 View ahead & right next ⅓ mi: angular unconformity. Atop flattish surface beveled across east-dipping, bedded Carmel Fm. is dark layer of basaltic bouldery gravel, overlain in turn by buff-colored local stream deposits.
7.7 Entrada/Carmel contact right.
8.0 Two parking choices: Here pull well off pavement on wide *left* shoulder. Or:
8.1 Just beyond left area, park off *right* shoulder.

STOP 3.1. Climb to top of terrace south side of hwy (fig. 1).

Westbound from the Henrys, G.K. Gilbert camped along the Fremont here. In his notes on the morning of September 1, 1875 (Hunt, 1988, p. 99–100):

> *We at once enter the cañon. . . . The route is impassable at a high stage of the river. There is no well established trail through the cañon as there is through [Pleasant] Creek Cañon. As in that cañon the gravel [here] is chiefly trachyte and the same shows on the benches at the sides.*

A. Bedrock & structure. By a brilliant red shaley Ss at entrance of Green River's gorge across Uinta Mtns, John Wesley Powell on his 1869 Colorado River exploration named it "Flaming Gorge." That place is 220 miles to the NNE, but with the Powell Survey's keen sense of regional stratigraphy Gilbert (1877, 1880) called the reddish unit just east of here "*Flaming Gorge Group: arenaceous shales of badland sandstone, purple and white at top and red below*". In just ¾ mile through a monoclinal limb far steeper than this one, Flaming Gorge descends downsection Morrison/Entrada/Carmel/Navajo/Chinle/Moenkopi/Permian (Hansen, 1955). Except for missing Wingate and Kayenta, that section resembles the inclined section here along Fremont River. Gilbert's color description matches what is today distinguished as Summerville/Curtis/Entrada.

B. Deep Creek gravel. Across Fremont to N are patches of basaltic gravel delivered toward the Fremont from the north. Terraces west of South Desert form an ascending flight 9 to 67 m (30–220 ft) above adjacent Deep Creek. There are two discontinuous but notable high benches at roughly 130 and 90 m above Deep Creek and descending along Carmel rock belt on west side South Desert at a little steeper than the gradient of Deep Cr. Gravel of highest terrace is 5 m thick over unconformity beveled in ***Jc***. Largest basalt boulders are 55–120 cm ID, and almost all clasts are sparse in phenocrysts and non-megacrystic (Th. L. Mtn source). Caliche underplaster at least as thick as 1 cm. Clasts of very hard (quartzitic) red-pebble conglomerate as large as 35 cm ID, chert, and other resistates.

Deep Creek now carries little black gravel: its bed is of reddish sand. This is typical of all stream, Fremont River and all its large tributaries. Each major boulder bench probably records a level of Deep Creek when it received a particularly large a glut of boulder gravel slushing down from Thousand Lake Mtn.

In the two prominent knolls overlooking east side of S. Desert, basalt all of sparsely porphyritic (5–15%) non-megacrystic type, largest boulders are round to subround as large as 0.6 to 0.9 m ID, but one is 1.2 m. Cuts in west side show gravel is clast supported. Northern knoll show gravel as thick as 9.9 m over bedrock ***Js***, in southern knoll about 5 m.

C. Gilbert's monoclinal shifting. Gilbert (1880, p. 129–132) argued how in moderately to steeply dipping strata streams once positioned in weak beds (shale) stay there, for as the whole landscape lowers they shift downdip with structure (fig. 20):

The tendency of waterways to escpe hard strata and abide in soft . . . , he elegantly put it.

This tendency is illustrated nicely here by two high and several lower basalt-boulder terraces overlying the Carmel and steeping down west toward the floor of South desert. This cannot but be a record of Deep Creek Thus during the last 150 m downwasting of these tilted rocks, here is a clear record that Deep Creek shifted progressively east—as the Entrada rock belt itself has shifted downdip east (fig. 21).

The two knolls on east rim of South Desert must not be of Deep Creek, but a drainage east of Deep Creek (fig. 21), probably the Hartnet, since diverted farther east during incision of complicated structure there.

D. Terrace and deposit here: Unconformity beveled across east-dipping Entrada Ss (Jurassic) 30 m or so above present floor of Fremont River is overlain by cobble gravel of mainly basaltic-andesite clasts. It carries subround (dominent) to subangular boulders as large as 0.75–0.9 m ID. Only about 1 in 10 basalt clasts are megacrystic (Boulder Mtn lithology) with crystals to 1.5 cm. Most clasts are sparsely porphyritic and non-megacystic (Thousand Lake Mtn lithology). When the Fremont flowed at this erosional level, boulder flows must have come down Fremont mainstem from the west, but even larger or more frequent ones flowed down Deep Creek to South Desert from the north—overwhelming the western lithology with the northern one.

This Fremont R. basaltic deposit is 1.5–2.5 m thick, capped in turn by light-colored sand and gravelly sand 2.5–6 m thick carrying only local sandstone flags (of ***Je*** and ***Jc***) and finer debris, no basalt. This overlying debris is deposit of local small stream off dip slope of WP Fold that spread as sidestream fan out onto former valley floor of Fremont R.

8.1 Resume eastbound Hwy 24.
9.0 Notom Road.

> ***NB mileage:*** *Current mileage count continues down the Fremont on Hwy 24. Endpoint of trek south will end either at Notom Bench or Oak Creek benches, mileage thus uncertain (and if a time problem, this stop will be shed). South trip is set between horizontal lines. Its separate mileage starts 0.0 at this intersection.*

Day-3 South trek on Notom Road. Mileages approximate.

MILES

0.0 Intersection UT Hwy 24 and Notom Road. Head south on Notom Road. On the east: Overlying the reddish bedded Entrada is more massive white Curtis Ss, that in turn overlain by reddish thin-bedded Summerville Fm (siltstone & mudstone).

0.25 Over next ⅓ mile small ravine west reveals same sequence as at Stop 3.1: atop beveled Carmel Ss a dark bed of basaltic gravel (thinner, only 1–2 m here), and that overlain by several mtrs of light-toned angular-flag gravel. We being here a mile east of Stop 3.1, this capping of local-stream gravel is an extensive fan from the west.

0.6 Over next ⅓ mi, the local Ss-flag gravel directly overlies beveled ***Je***: underlying Fremont R. gravel is gone—pinched out.

1.8 But upon descent toward Pleasant Cr., black-basalt gravel again. The 'basalt-free zone' behind us reveals an inconspicuous divide between the Fremont and Pleasant Cr. over which (at this general erosional level) neither stream crossed.

2.0 Pleasant Creek.

2.2 We've crossed bedrock contact ***Jc/Je*** into white Curtis Ss. Now largest black boulders are 1.0 to 1.5 m ID, considerably larger than nearby in Fremont valley Stop 3.1. Also different is that all of these are of megacrystic variety—all from Boulder Mtn, none from Th. Lake Mtn. Thus though at similar level to Stop 3.1 deposit, here we are in a different boulder stream.

2.4 A few different levels of black-boulder terraces overlook Pleasant Cr. west of us. Largest boulders 1.0–1.5 m ID.

3.8 Former village Notom to west. Here Capitol Wash (thus pre-1962 road through reef) enters Pleasant Cr. Capitol Wash crosses the reef but not Miners Mtn (heads on it). No black boulders from Boulder Mtn came down it: they come from farther south.

4.6 Largest black boulders on terraces west 1.0–1.5 m ID—same as below Notom.

5.6 Begin ascent of Notom Bench.

5.8 N. brow of Notom Bench.

(***Alternate STOP 3.2.***). Pleasant Cr. enters from gash through reef to west. Pleasant Cr. crosses Miners Mtn as well, heading on Boulder Mtn, whose boulders have come down this way. Though from here Pleasant Cr. now flows north along this strike valley in the Entrada, transverse Notom Bench records Pleasant Cr. at this 5500 ft level flowing across this valley, over the broad ridge to east (of Morrison Fm), and to Sandy Cr into the next (Mancos shale) strike valley 2½ miles east of here.

But like the area 5½ mi north of here, the surface of Notom Bench is all of local buff sand and sandstone flags. Thick extensive terraces of basalt gravel lie along Pleasant Cr a mile and more west, but here beneath the capping sandstone gravel is a wedge of basalt gravel. Basalt clasts are worn to subangular to subround shapes, and largest here are 0.9–1.5 m ID, most or all of the porphyritic, megacrystic variety—plagioclase crystals >20%, conspicuous, as large as 15–20 mm. A few rounded nonbasalt pebbles here, but none of the large angular chalcedony, which seems limited to the basalt-boulder gravel from northern sources.

6.0 Crossing of dirt road along top of Notom Bench.

6.8 Having descended off Notom Bench (with no more basalt in sight—it went north with Pleasant Cr.), nice outcrop east of ***Je/Jc/Js***—the white Curtis Ss with sweeping eolian bedding interrupting the apparently fluvial well-bedded reddish underlying Entrada and overlying Summerville Fms.

8.3 Just east of road, outcrop shows stacked graded beds of the Entrada—medium ss grading up to shale—several successive cycles each a few meters thick.

8.8 Cottonwood Wash heads in but does not cross the reef: it carries no basalt clasts.

9.8 Fivemile Wash also heads in the reef, does not cross it: no basalt clasts.

12.6 Sheets Gulch is a big canyon, but it too heads in the reef, does not cross it: carries sandstone flags but no basalt.
13.2 On approach to Oak Cr, basalt boulders appear again, on bench to east.
13.7 Cross Oak Creek.
14.0 N. brow of broad terrace from Oak Creek.

STOP 3.2. Three terraces: lower two terraces (here) spaced 5 m or so apart about 160 ft (50 m) above Oak Cr. and 200 ft (60 m) above Sandy Cr. just east (fig. 5). Highest broad terrace ⅓ mi to south is another 100 ft (30 m) yet higher. Each has black boulders as large 1 m ID but most are much smaller.

Substop A. Lowest (youngest) terrace has best roadcut, showing about 1.5 m of gravel over surface beveled in highly weathered Entrada Ss. Boulders are typically subround and clast supported. A few percent of angular local buff to reddish Ss clasts. Boulders apparently all of porphyritic, megacrystic variety. Caliche undercoatings as thick as 15 mm.

Terraces must represent 3 flows of distinctly different heights (thus ages?). Roundness & clast support indicates fluvial flood rather than debris flow. Bouldery surface far more resistant to erosion than adjacent bedrock, whether shale or sandstone.

Continue up road.

14.35 Climbing to highest terrace. At fork in road, turn left.
14.6 East side of high terrace.

Substop B. Striking view east of east-dipping section from Entrada Ss to MesaVerde Ss. Prominent sandstone cliff-formers are Morrison, Ferron, Emery, MesaVerde. (All but the MesaVerde we shall shortly see closer along our Fremont R. route.) Beyond the Tertiary intrusion—GK Gilbert's (1877, 1880) classic laccoliths—of the Henry Mountains. Much of Mesozoic section we've ascended through from Fruita is sharply upturned around the Henry Mtns intrusions.

> [17 June 1872. (A.H. Thompson party)]
> *Keeping along the divide we had comparatively easy going. About noon we arrived at the edge of an intervening valley, the wind blowing a fierce gale. Crossing this depression, we reached a small creek at the foot of the second mountain from the north (now Mt. Pennell) and climbed its slope seventeen hundred feet to a beautiful spring, where we camped.*
>
> — Frederick Dellenbaugh (*A Canyon Voyage*) 1908

14.6 Turn around and retrace route north past Notom to Hwy 24.
29.2 Intersection UT Hwy 24. Turn right.

End of Notom-Road trek.

NB: resume Fremont R. mileage at 9.0

9.1 Lower part of east scarp of South Desert is the reddish, bedded Entrada. Overlying that is more massive white Curtis Ss, that in turn overlain by reddish Summerville Fm (siltstone & mudstone).

9.2 Approx. base of Morrison Fm, Salt Wash Mbr. that overlies the Summerville Fm (*Jms*/*Js*). The Morrison is highly heterogeneous (conglomerate, sandstone, weak shale).

9.5 East boundary of Capitol Reef National Park (restrooms).

9.6 Variegated shale of *Jms*

11.0 Base of upper (Brushy Basin) Member of Morrison Fm.(*Jmb*). On left, landslide in weak Morrison Fm. The thick bentonite-shale layers of the upper Morrison forms badlands.

11.8 River ford west-access road left. Hwy 24 bumpy on weak, deforming Morrison shale.

12.3 River ford east-access road "Y" left. For Stop 3.3 a few vehicles may park on sides of "Y." Beware fast traffic around highway curves. Road climbs & curves up Morrison Fm. to terrace.

12.45 Park off right shoulder. Beware fast traffic.

STOP 3.3. Climb southwest up to terrace top. Note character of the silicic conglomerate of the Morrison Fm.

Basaltic-andesite gravel of this terrace 115–130 m (380–420 ft) above Fremont River overlies an unconformity cut in Morrison Fm (upper Jurassic) sandstone & conglomerate. On way up one sees that the gray-white conglomerate of the Morrison Fm. fractures *around* pebbles. It cannot be the source of the reddish very hard quartzitic conglomerate clasts (fractures *through* pebbles) that travel with basalt-boulder gravel from the northern source.

Largest boulders on terrace typically 50–70 cm ID but rare ones to 1 m ID. Though we are on south bank Fremont River, almost all basalt clasts are of non-megacrystic variety (from Th. L. Mtn). Shape range subangular to round, dominently subround, surely waterlaid.

View NNW: high broad bench 630 ft (190 m)_above Fremont R. is cut in Morrison (but E end in lowest of Mancos shales). Bench is overlain by thick sequence of black boulder-cobble-pebble gravel whose clasts are typically subround, no larger than 1.1 m ID, and clast supported (*thus waterlaid*). Sand-rich interbeds indicate several separate coarse-gravel beds consititute this gravel as thick as 10 m. Most basalt clasts there are of non-megacrystic variety. *(Interpretation: at this level several separate large floods issued from catastrophic mass-wasting events on Thousand Lake Mtn).*

Broad bench to NNE is merely outlier of that just west. Behind this north, several of *highest* points of land are capped by such gravel, every one I've examined of waterlaid gravel.

Distant views N and E of bedrock sequence Morrison to upper Mancos Group thick sandstone Formations—intruded at Henry Mtns by Tertiary.

12.45 Continue east on Hwy 24.

12.65 Old Notom Road enters from right (old "highway" via Capitol Wash before 1962). Here Morrison Fm. (***Jmb***) passes beneath base of Mancos Shale, Tunuck Shale Mbr. (***Kmt***) forming bluish plain. Caineville 'Reef' hogback ahead is Ferron Ss Mbr of Mancos Shale (***Kmf***). The Mancos comprises 3 great shale beds summing to 2400–3000 ft thick, each shale overlain by a cliff-forming sandstone 300–400 ft thick (uppermost is MesaVerde Ss). Gilbert (1877, 1880) described all six but named the sandstone beds with the underlying shale; his local names stuck to the shale members (Tunuck, Blue Gate, Masuk). Gilbert's underlying 'Henry's Fork Conglomerate' (a Powell survey regional name: overlies red-rock belt at mouth of Flaming Gorge) later became the Morrison Fm.

13.4 Start up through 'blue dugway' pass in ***Kmt***. Relic of old dugway.

14.3 Pass. Over next ½ mile, dugway relics both sides—the left one for when snow lingered on shaded main track.

15.35 Fremont R.

16.3 Start up stretch over ***Kmt*** shale. Next ¾ mi relics of old dugway.

18.7 Gap through east-dipping Ferron SS Member of Mancos Shale (***Kmf***). The Ferron holds up 'Caineville Reef' hogback. Caineville Wash road is way out on FOTP optional Day 4.

19.0 From here eastward through "Blue Gate" road is in Blue Gate shale Mbr of the Mancos Shale (***Kmb***), eroding to badland hills. The Blue Gate shale is far thicker than the other two Mancos shale members. Big cliffs above (N. Caineville Mesa; S. Caineville Mesa) are of Emery Ss Mbr. of the Mancos (***Kme***).

19.9 Through this stretch several small remnants both sides of black-cobble terrace over surface planed in Blue Gate shale.

21.0 At "Blue Gate," N. and S. Caineville cliffs (***Kms***) are 2 miles apart. Approximate axis of broad N-S syncline.

24.2 Pull off on shoulder where you can safely (may be difficult).

STOP 3.4. Views of Blue Gate. Badland slopes developed in Blue Gate shale Mbr. overlooked by high cliffs of Emery Ss Mbr. Structural relief across Waterpocket Fold from crest of Miners Mtn anticline to trough of Blue Gate syncline is 8000 ft (2440 m). Factory Butte to north is picturesque outlier of Emery Ss over Blue Gate shale (***Kme/Kmb***) along northeast trend of syncline. As Landsat image reveals, from Blue Gate the N-S synclinal axis turns northeast. North of Fremont River, Waterpocket monocline divides around a low-relief anticlinorium: one arm of monocline continuing NW as Waterpocket, the other branching NE to join great monocline along SE side of San Rafael Swell.

Having crossed a scarcely perceptible synclinal axis, we are now in its gentle east limb. Proceeding east, we'd march slowly downsection: lower Mancos, Morrison, etc. until at Hanksville (15 mi east) we'd return to the Entrada (of South Desert).

Continue east on UT 24.

25.4 Begin topographic ascent—stratigraphic descent—to Ferron Ss (***Kmb/Kmf***). In roadcuts rocks dip gently west.

26.4 At top of grade, gravel roads join. Turn onto south one, which ascends to terrace surface.

26.8 Fork in gravel road. Take right one leading SW.

27.1 Road ends in a loop at hut by Caineville's gravel airstrip. Park and walk south 300 yds to SW edge of terrace overlooking Fremont River.

STOP 3.5. 'Airport' terrace.

Views north of Factory Butte and east of Blue Gate and the Caineville Mesas.

Terraces are few and small in Blue Gate, where proximity of ***Kme*** cliffs keeps slopes steep and erosion active. But where valley widens east in Blue Gate shale ("Upper Blue Hills"), broad terraces are preserved at 3 levels. Once again from G.K. Gilbert's field notes (Hunt, 1988, p. 95):

> *August 30 [1875]. In the valley of the D.D. [Dirty Devil, = Fremont R.] between the Twins [Caineville mesas] is a mesa = old floodplain capped with debris from the west, chiefly Aquarius trachyte. It is 200 ft high and there is another below it of half the height.*

Here on upper terrace about 260 ft (80 m) above Fremont River encanyoned in Ferron Ss. Gravel is 2–3 m thick over ***Kmb*/*Kmf*.** Gravel is mixed lithology but remains heavily of basaltic andesite. Largest basalt clasts are 45–60 cm ID and abraded into subround to round shape—thus both considerably smaller and rounder than those at Stop 3.1 at South Desert 23 mi (37 km) upvalley. Less than half the basalt clasts are megacrystic (Boulder Mtn) variety. Many quartzite and chalcedony clasts to 12 cm ID—also much smaller than at Stop 3.1.

Cosmogenic dating. Repka and others (1997) obtained a suite of 29 'amalgamated' ^{10}Be and ^{26}Al cosmogenic dates on three terrace levels through Blue Gate. They correlated them with 3 glacial stages. Dave Marchetti and Thure Cerling will summarize these techniques and discuss these data (fig. 22).

Terrace level	**Height above R. (m)**	**Age (ka)**	**Glacial stage (RkyMtn terminology)**
4	140	151 ±24	Bull Lake
3	80	102 ±16	early Pinedale
2	50	60 ±9	mid Pinedale

End Day 3.

Close of 44th reunion of RkyMtn FOTP (except optional Day 4 north).

Bon voyage!

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Figure Captions

Figure 1. Index map: Heavy lines, roads. Light lines, rivers and creeks. Dots, stops for FOTP conference. BM = Boulder Mtn; TLM = Thousand Lake Mtn; Towns are square: Bicknell, Teasdale, Torrey, Grover, Notom, Caineville, and Fruita (nor square).

Figure 2. Stratigraphic column for Capitol Reef area, Permian to Cretaceous (from Billinsley and others, 1987).

Figure 3. Gradient of Fremont River upstream of Hanksville (David Marchetti).

Figure 4. Diagrammatic profile of lobate debris flows and wet debris flows shed from south margin of Aquarius Plateau (from Williams, 1984, fig. 3)

Figure 5. Distribution of drainages and black-boulder debris and terraces in upper Fremont R. and tributaries, Capitol Reef area (shrimp version of FOTP-stop poster).

Figure 6. Concept of floodplain meanders becoming incised meanders (from Stokes, 1969, p. 43).

Figure 7. William Lee Stokes' sketch of Sipapu natural bridge at Natural Bridges Nat'l Monument (from Stokes, 1969, p. 48).

Figure 8. Alcove arch (or blind arch, or niche arch) at in reisitant Wingate Ss developed upward into it from undermined weak Chinle shale, along North Wash (from Hunt and others, 1953, fig. 88).

Figure 9. Barrier Canyon Style rock art elements typical of the Capitol Reef area (no scale).

Figure 10. Southern San Rafael Fremont Style rock art panels in the Capitol Reef area (no scale).

Figure 11. Early Historic period rock art panels in the Capitol Reef area (no scale).

Figure 12. Interpretation of Flint and Denny (1958) of Carcass Creek fan as drift (glacial till and outwash).

Figure 13. Reinterpretation of Carcass Creek fan as debris avalanche and debris flow, 1998 version.

Figure 14. Torrey (Garkane) dam site geologic sketch by Ben Everitt (from Everitt and others, 1997, fig. 4).

Figure 15. G.K. Gilbert's concept of a pediment on flank of Henry Mountains. Beveled-off upturned strata are Navajo Ss (or Carmel Fm) and Entrada Ss and capping layer is coarse 'trachyte' gravel. Gilbert's called the feature a 'hill of planation' (Gilbert, 1880, fig. 63)

Figure 16. Petroglyph panels from the Southern San Rafael Fremont style "type site," Capitol Reef National Park (no scale).

Figure 17. Relation of some boulder-deposit surfaces to profile of Fremont R. (Dave Marchetti).

Figure 18. Summary of 3He exposure ages (ka) for Hickman moraine and Johnson Mesa samples (the dashed line separates the two different sampling locations). The Johnson Mesa terrace samples are subdivided into boulder and desert pavement samples as marked. All Hickman moraine samples were from boulders. Error bars are +/- 10% of the calculated age. Age ranges of the major Rocky Mountain glacial cycles are highlighted in gray and labeled (dates according to Phillips et al., 1997). NOTE: Other than to visually separate sampling location (Hickman vs. J. Mesa) and separate Johnson Mesa sample type (boulder vs. desert pavement), the sample location along the Y-axis is meaningless.

Figure 19. Field sketch of 2 successive incised meanders cut into Navajo Ss (*Jn*) in Grand Wash, views downstream east. Both are of ingrown type. Stream course drawn between them at erosion level 300 ft above present would be straighter than present meandering course of Grand Wash.

Figure 20. G.K. Gilbert's concept how during degradation of tillted strata drainage divides are impermanent and weak beds tend ot capture drainage (from Gilbert 1880).

A. Monoclinal shifting of waterways: stream *B* in resistant bed downcuts vertically until intersection weak strata while stream *A* in weak strata stays there (Gilbert 1880, fig. 66).
B. Shifting of divides but maintaining profile (Gilbert 1880, fig. 69).

Figure 21. Gilbert's monoclinal divide shifting applied to South Desert area.

A. As erosional level is successively lowered over time, streams positioned in weak strata shift downdip, riding the tops of resistant Carmel (Jc) and Morrison (Jms) beds. Streams occasionally receive catastrophic flood of coarse gravel from events on Thousand Lake Mountain (black blobs)
B. Situation today. Stranded gravel benches are record of downdip migrations of Deep and Hartnet Creeks. The one overlooking Deep Creek from the east dowes not belong to it.

Figure 22. Age estimates for three best-dated terraces (2, 3, 4) shown against normalized $\delta^{18}O$ record; oxygen-isotope glacial stages numbered. The terrace ages correspond roughly to global ice-volume maxima in stages 4, 5d, and 6 (from Repka and others, 1997, fig. 7).

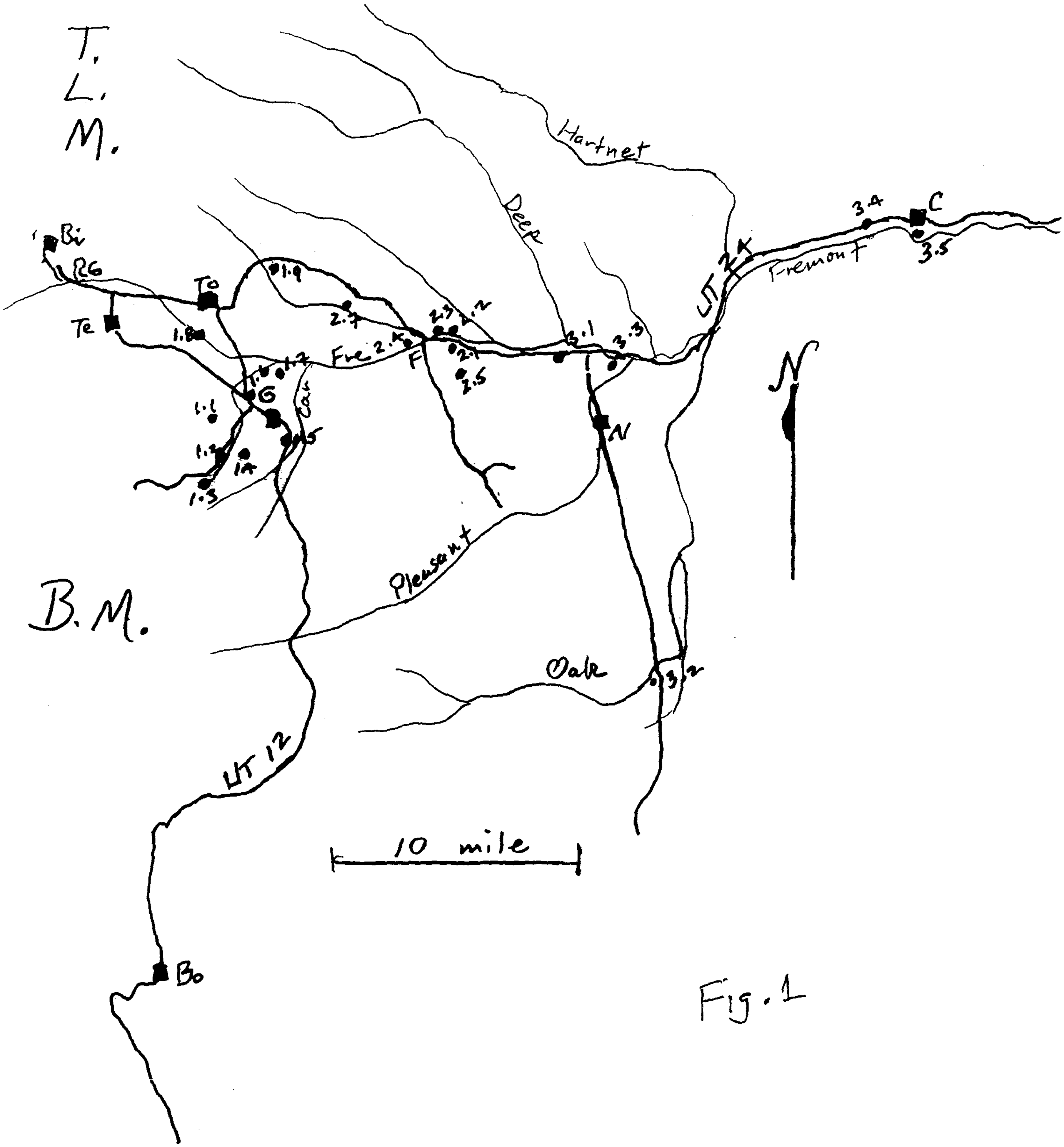

T.
L.
M.
Hartnet
Deep
Bi
RG
To
Te
1.9
2.7
1.8
Fre 2.4
F
2.5
3.1
3.3
UT 24
3.4
C
Fremont
3.5
N
G
1.1
1A
1.3
Cav
Pleasant
B.M.
Oak
UT 12
10 mile
Bo

Fig. 1

SYSTEM	FORMATION		SYMBOL	THICKNESS (feet)	LITHOLOGY
TERTIARY	FLAGSTAFF LIMESTONE		Tf	~500+	
TERTIARY / CRETACEOUS	MESAVERDE FORMATION		Kmv	300-400	
CRETACEOUS	MANCOS SHALE	Masuk Member	Kmm	650-750	
CRETACEOUS	MANCOS SHALE	Emery Sandstone Member	Kme	300-400	
CRETACEOUS	MANCOS SHALE	Blue Gate Shale Member	Kmb	1200-1500	
CRETACEOUS	MANCOS SHALE	Ferron Sandstone Member	Kmf	205-385	
CRETACEOUS	MANCOS SHALE	Tununk Shale Member	Kmt	540-720	
CRETACEOUS	DAKOTA SANDSTONE		Kd	0-150	
CRETACEOUS	CEDAR MOUNTAIN FORMATION		Kcm	0-166	
JURASSIC	MORRISON FORMATION	Brushy Basin Member	Jmb	200-350	
JURASSIC	MORRISON FORMATION	Salt Wash Member	Jms	100-500	
JURASSIC	SUMMERVILLE FORMATION		Js	50-200	
JURASSIC	CURTIS FORMATION		Jcu	0-175	
JURASSIC	ENTRADA SANDSTONE		Je	400-900	
JURASSIC	CARMEL FORMATION		Jc	200-1000	
JURASSIC / TRIASSIC	NAVAJO SANDSTONE		JTRn	950-1400	
TRIASSIC	KAYENTA FORMATION		TRk	350	
TRIASSIC	WINGATE SANDSTONE		TRw	350	
TRIASSIC	CHINLE FORMATION		TRc	500-700	
TRIASSIC	MOENKOPI FORMATION		TRm	800-1000	
PERMIAN	KAIBAB LIMESTONE		Pk	0-200	
PERMIAN	CUTLER GROUP UNDIVIDED		Pc	800+	

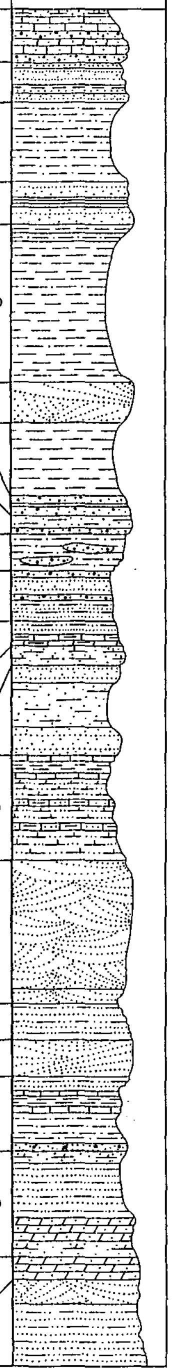


Fig. 2

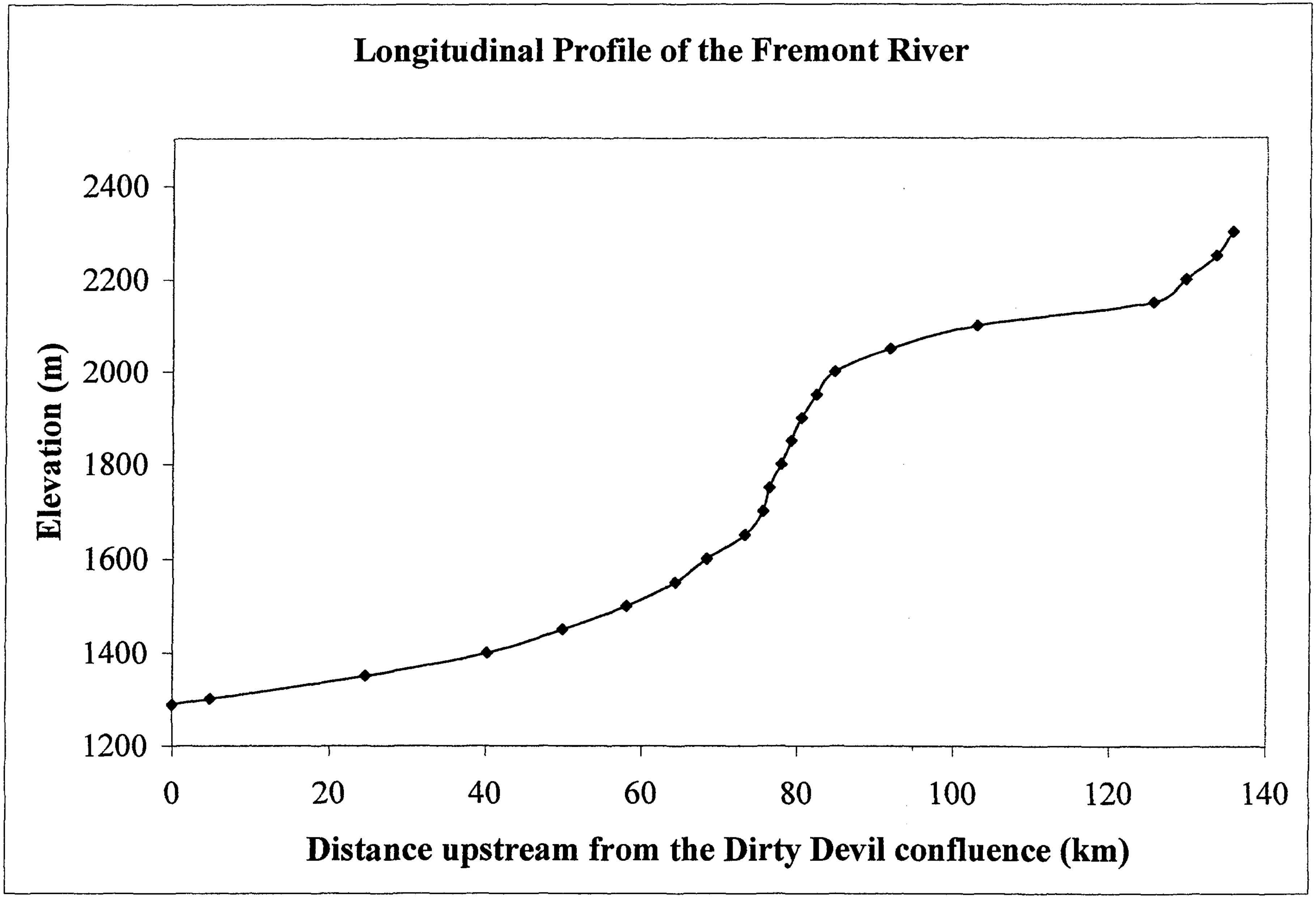

Longitudinal Profile of the Fremont River
Elevation (m)
2400
2200
2000
1800
1600
1400
1200
0
20
40
60
80
100
120
140
Distance upstream from the Dirty Devil confluence (km)

Fig. 3

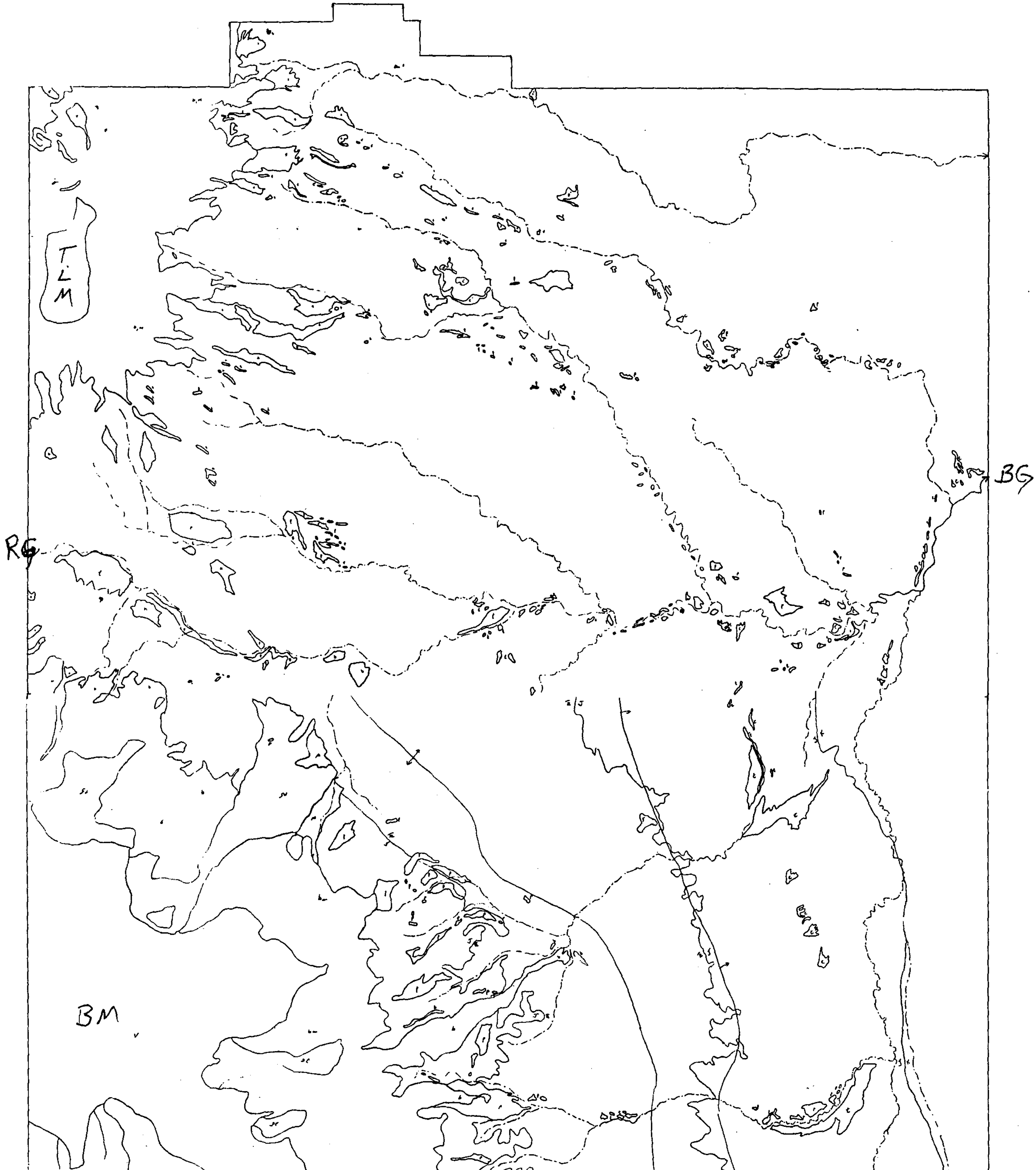
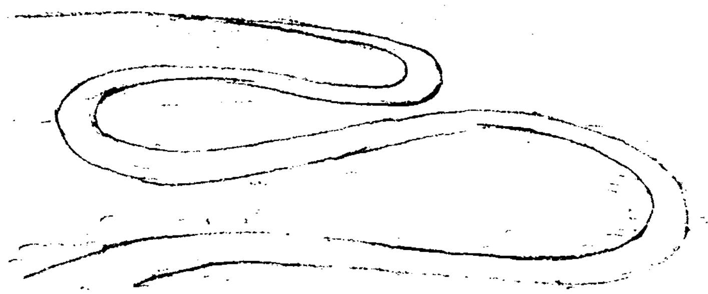
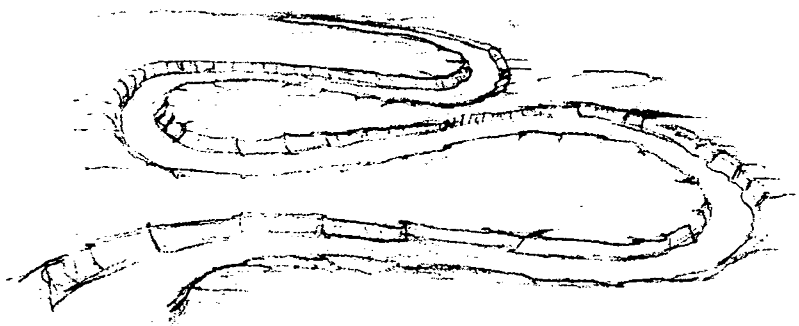


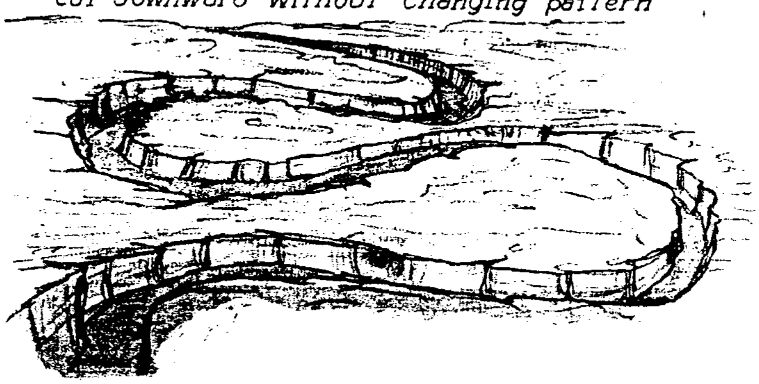
Fig 5



First stage—River meandering on low-lying plain



Second stage—Region is uplifted, river begins to cut downward without changing pattern



Third stage—River is completely enclosed in high canyon walls, but still follows the original curving course. This is the stage reached by many rivers in the Colorado Plateau.

ORIGIN OF INCISED MEANDERS

Curving rivers within deep canyons

Fig. 6

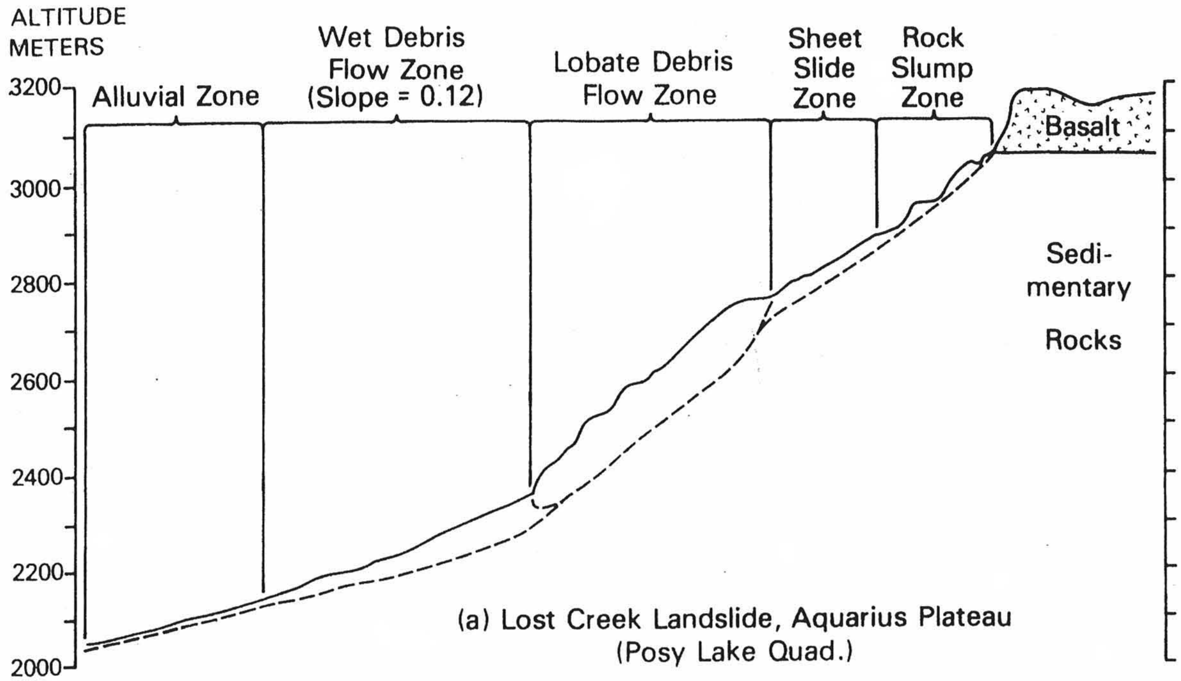
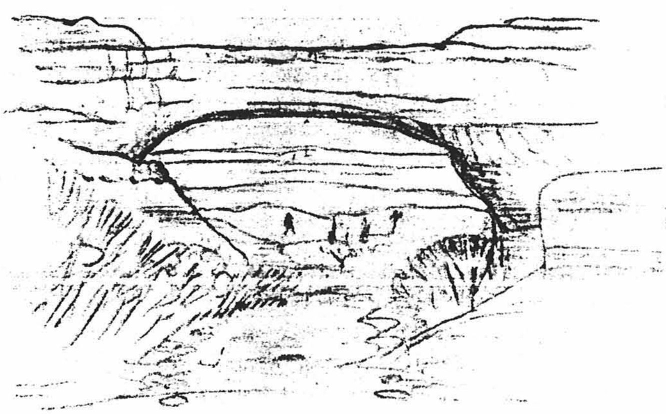


Fig. 4



SIPAPU NATURAL BRIDGE
268 foot span
167 feet from stream bed
to base of bridge
bridge 53 feet thick

Fig. 7

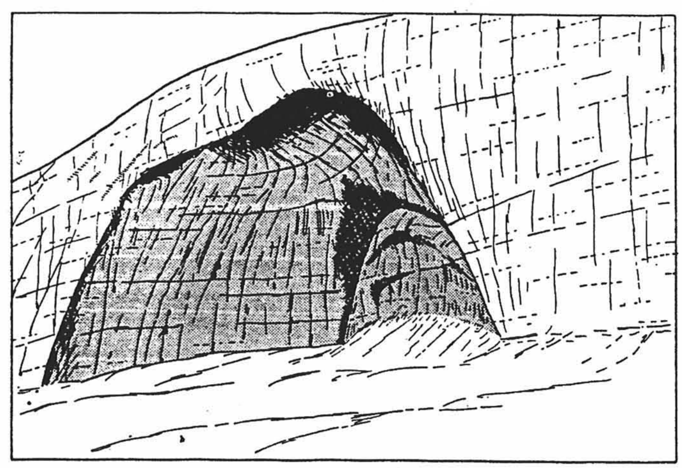


FIGURE 88.—Small alcove arch in Wingate sandstone, south wall of North Wash 1 mile below Hog Canyon. Sketch from photograph.

Fig. 8

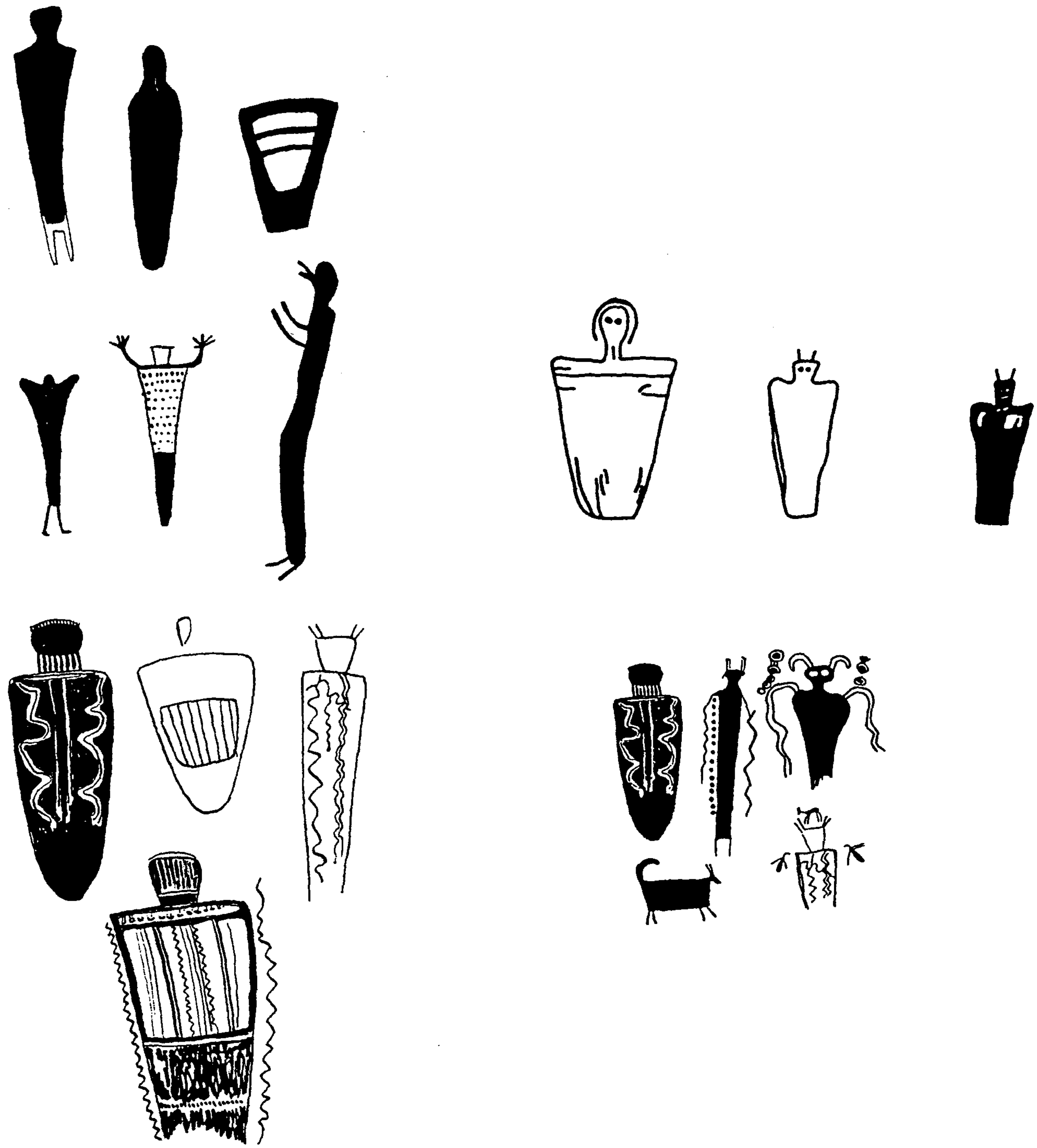


Fig. 9

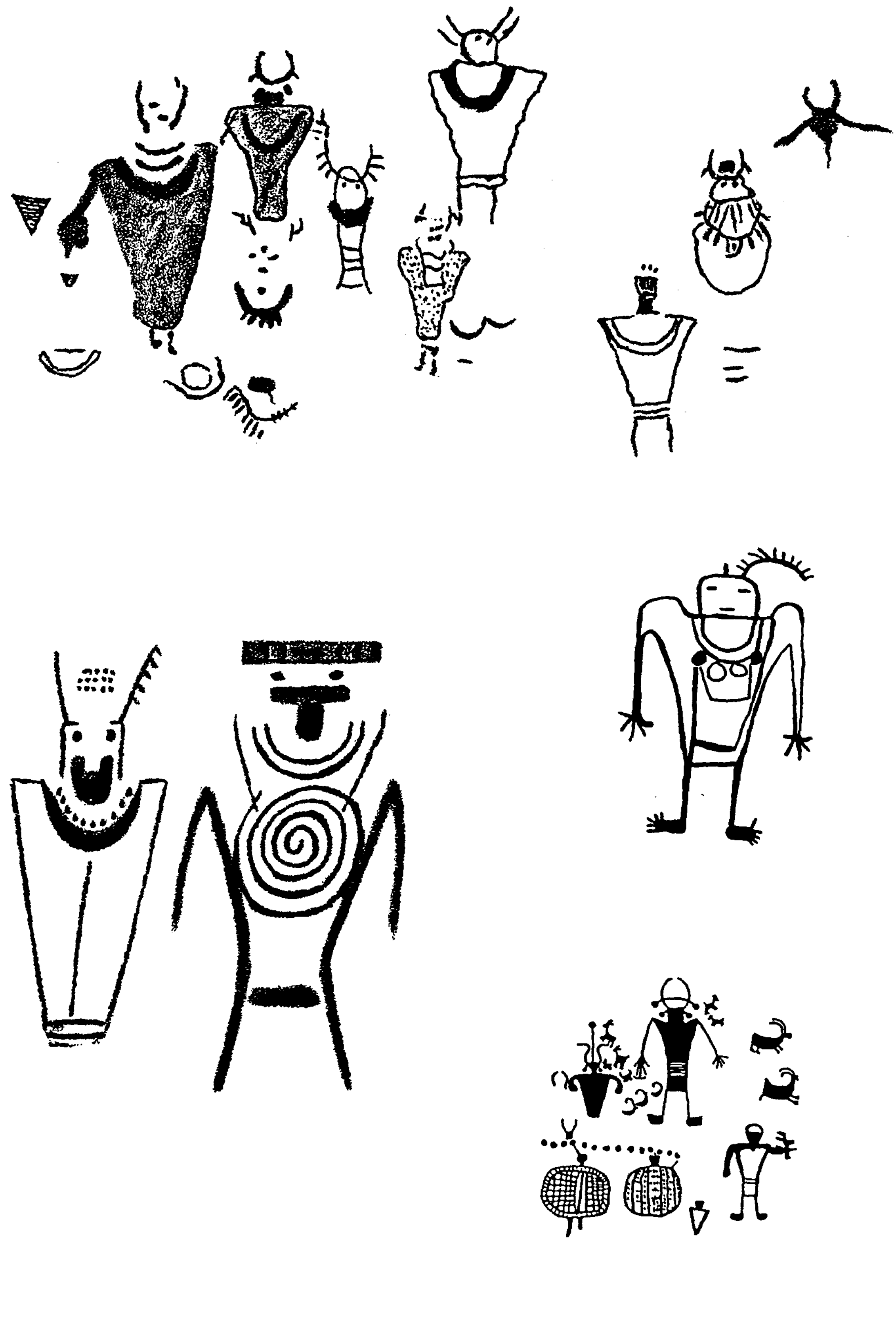


Fig. 10

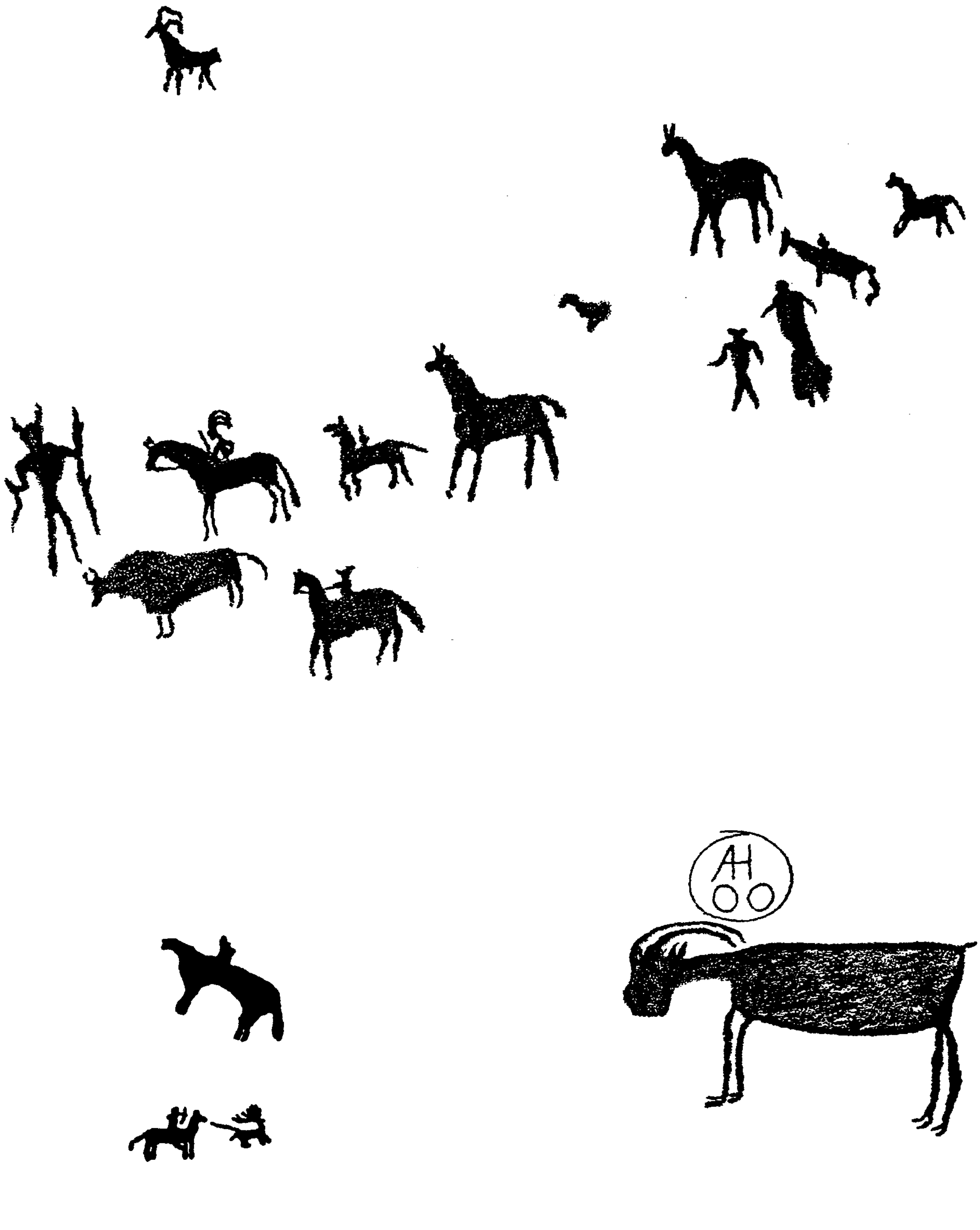


Fig. 11

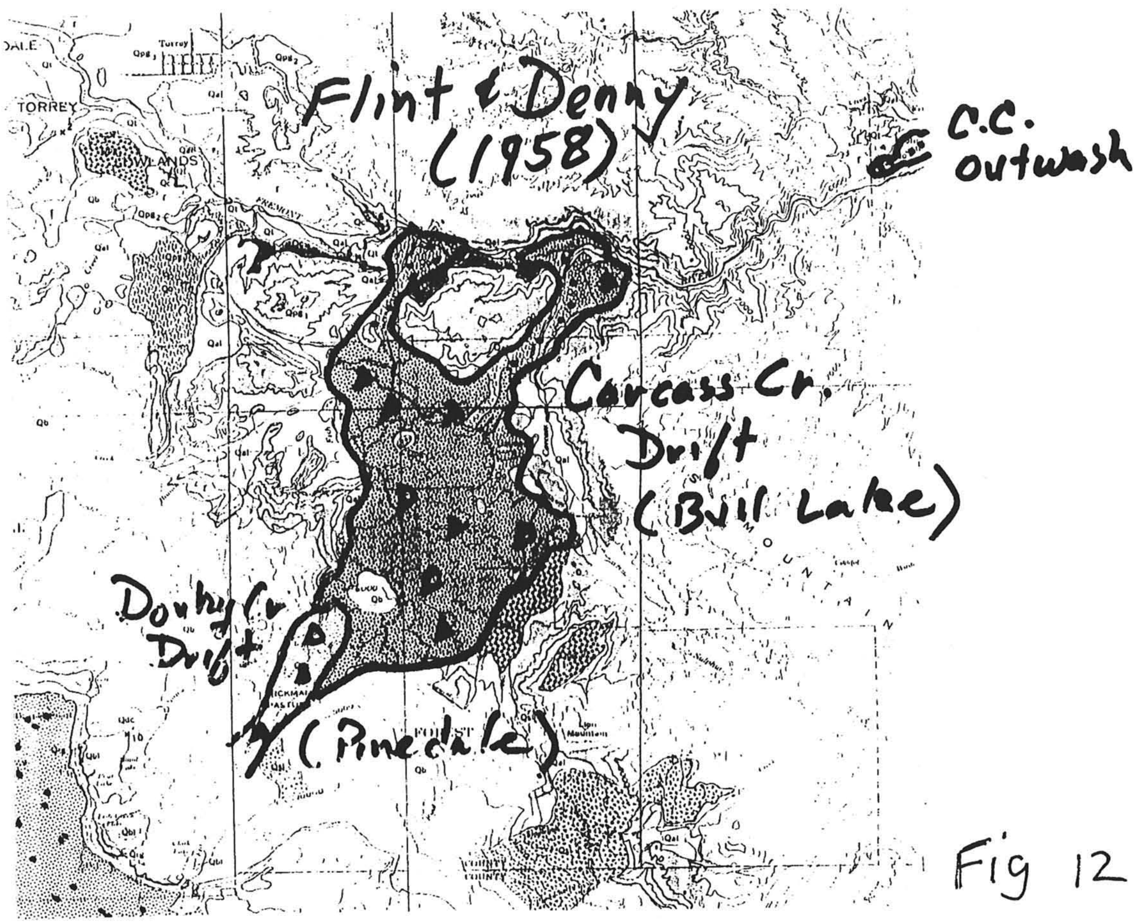

Flint & Denny (1958)
C.C. outwash
Carcass Cr. Drift (Bull Lake)
Dorhy Cr Drift
(Pinedale)
TORREY
LOWLANDS

Fig 12

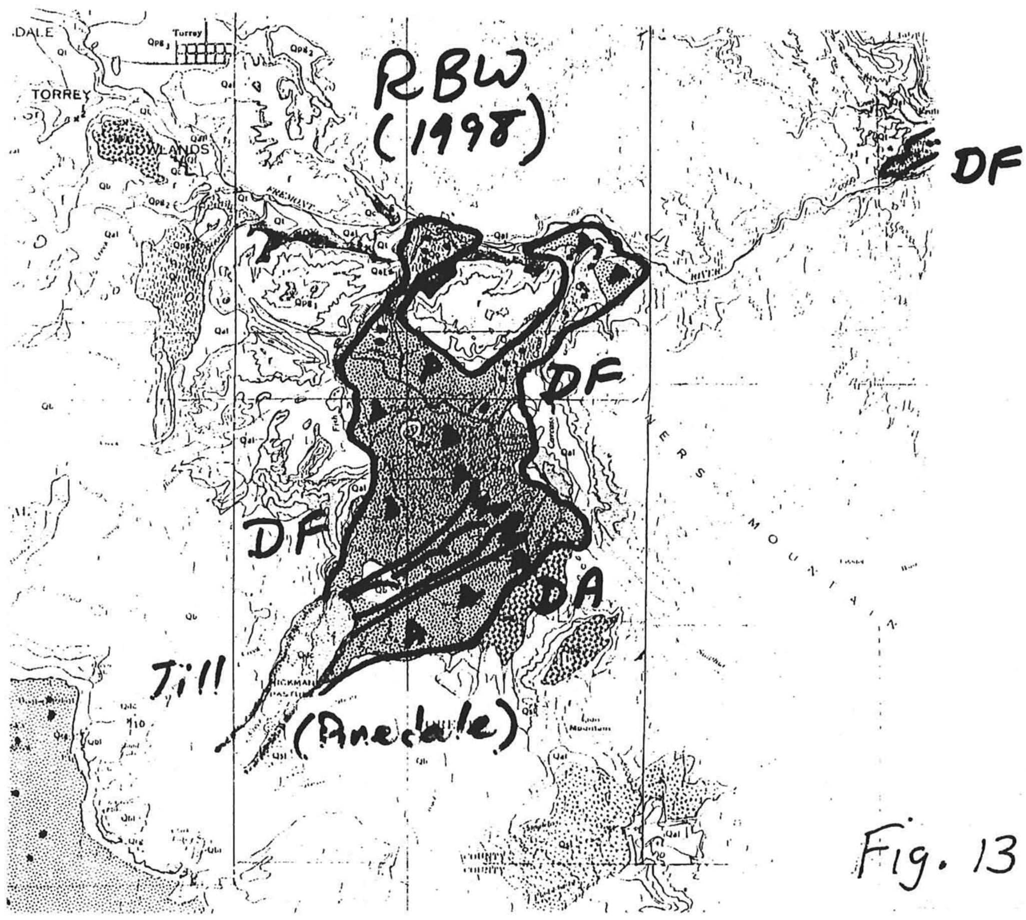

RBW (1998)
DF
DF
DF
DA
Till
(Pinedale)
TORREY
LOWLANDS

Fig. 13

TORREY (GARKANE) DAM SITE GEOLOGIC SKETCH

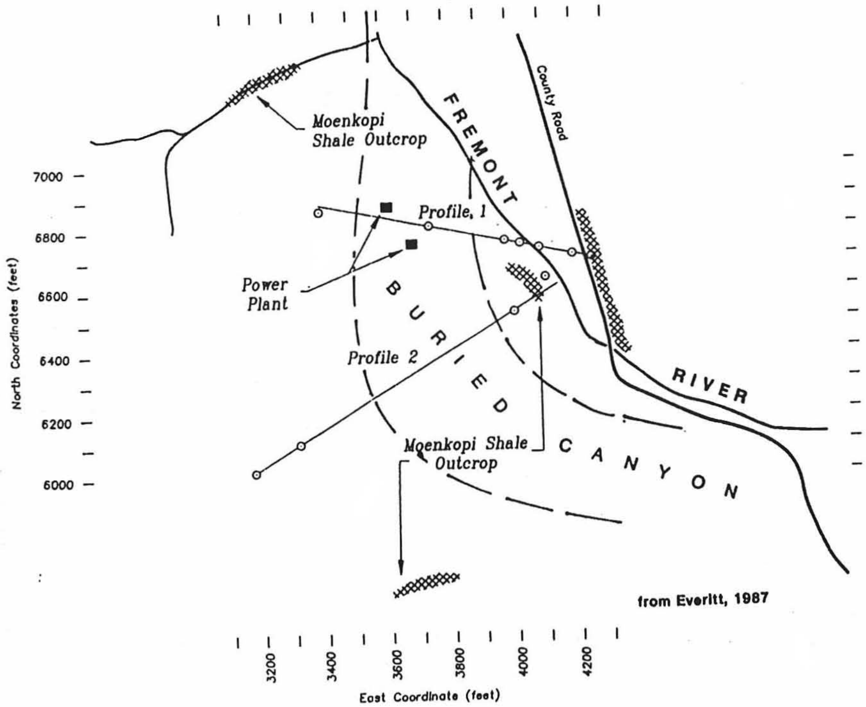


Fig. 14

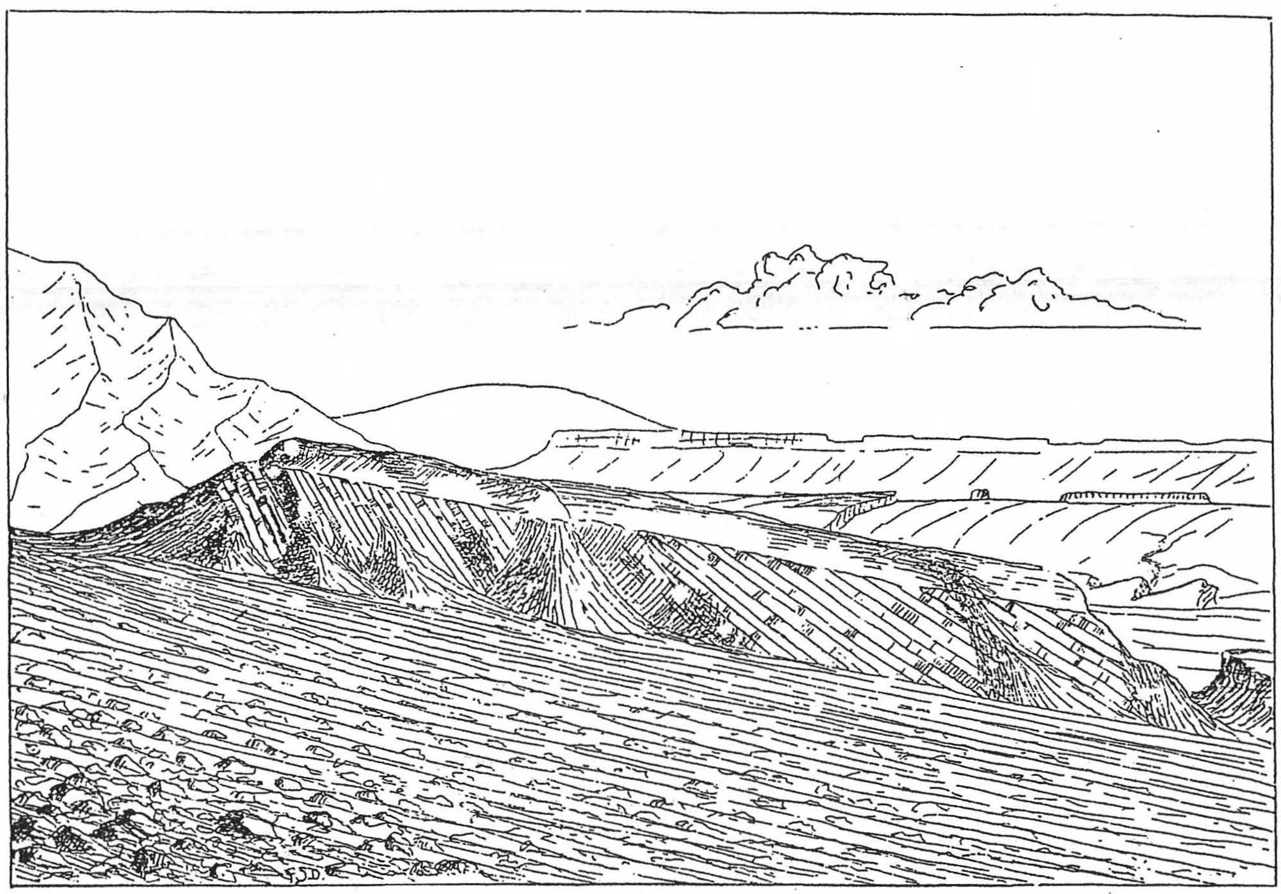


FIG. 63.—A Hill of Planation.

Fig. 15

Fig. 16

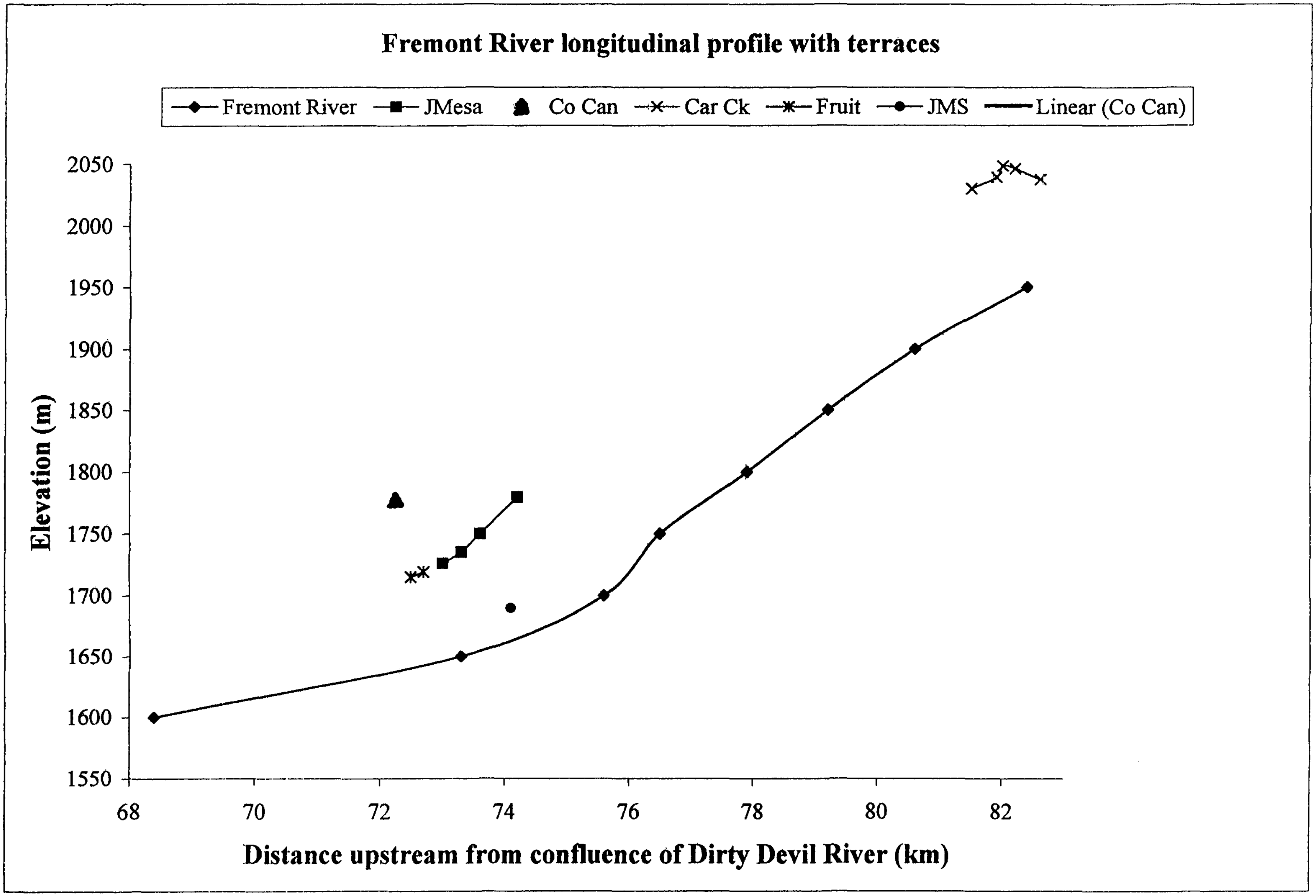

Fremont River longitudinal profile with terraces
Fremont River
JMesa
Co Can
Car Ck
Fruit
JMS
Linear (Co Can)
Elevation (m)
2050
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
68
70
72
74
76
78
80
82
Distance upstream from confluence of Dirty Devil River (km)

Fig. 17

Preliminary 3He cosmogenic ages (ka) for sampled surfaces in the Capitol Reef area

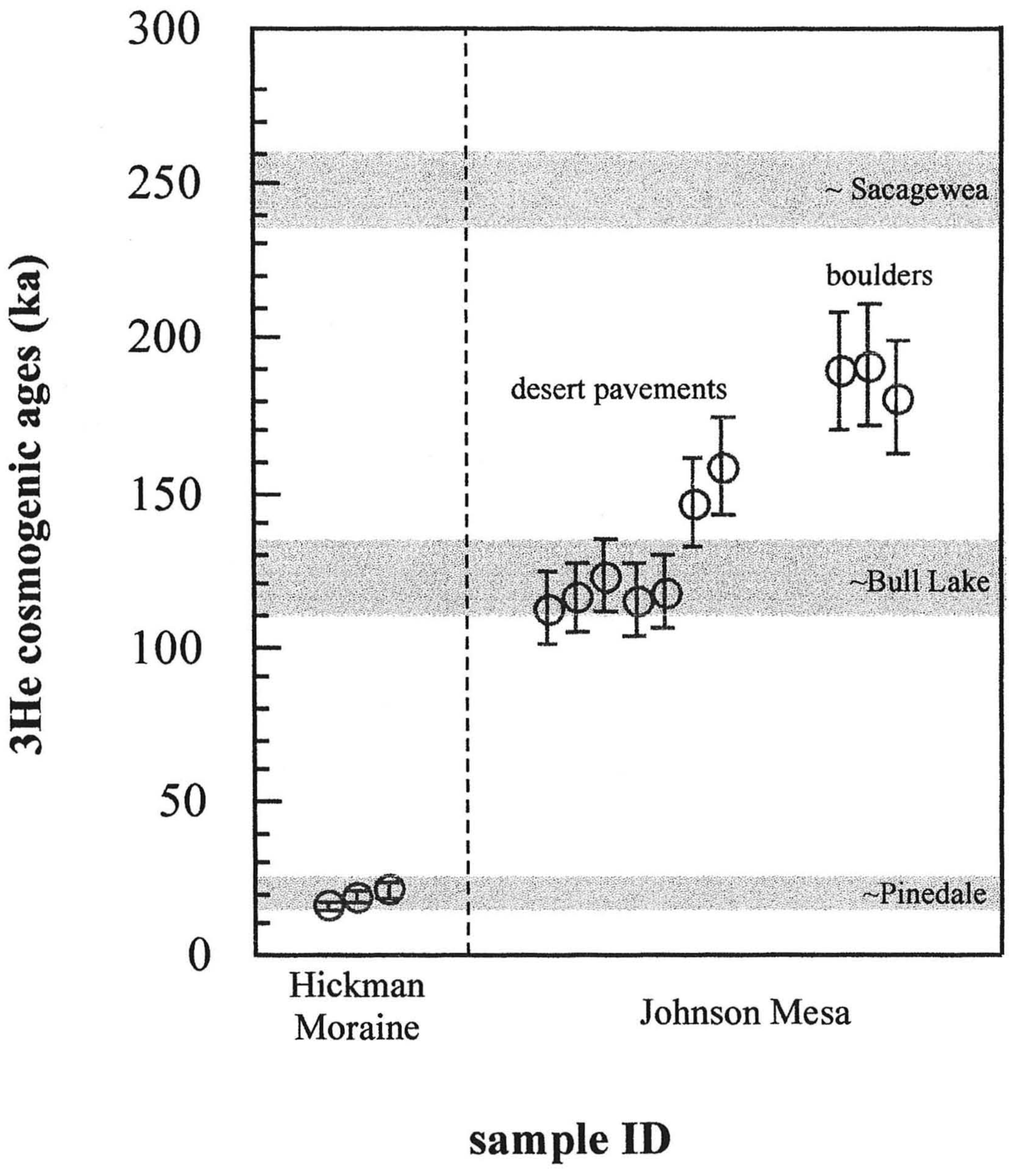


Fig. 18

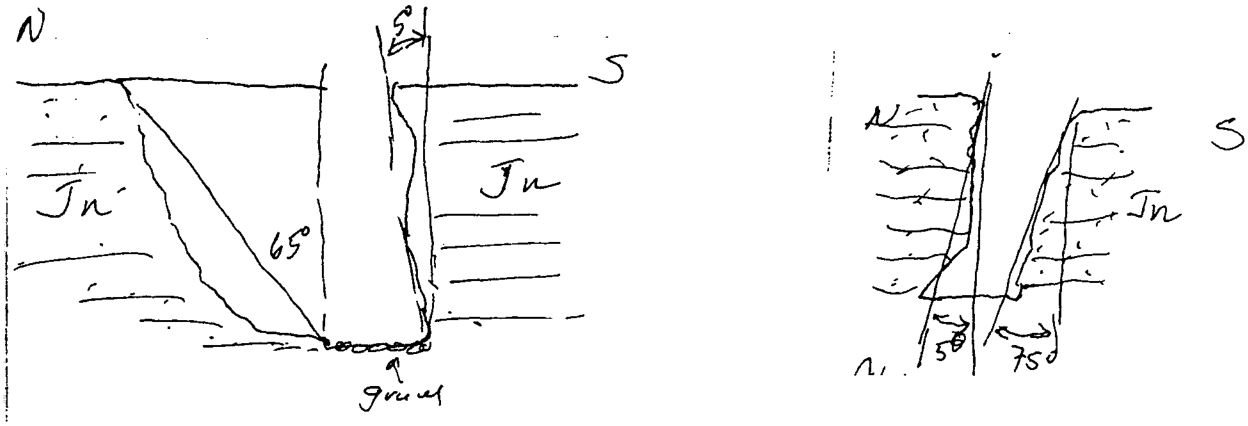


Fig. 19

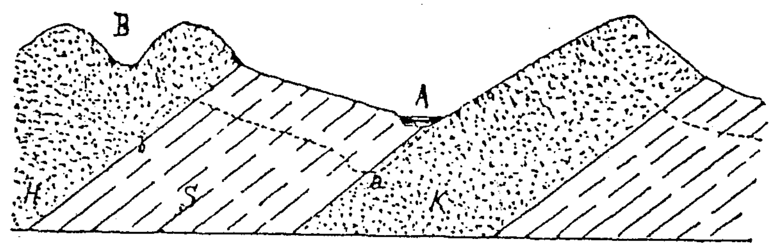


FIG. 66.—Cross-section of inclined strata, to illustrate Monoclinal Shifting of waterways.

Fig. 20 A

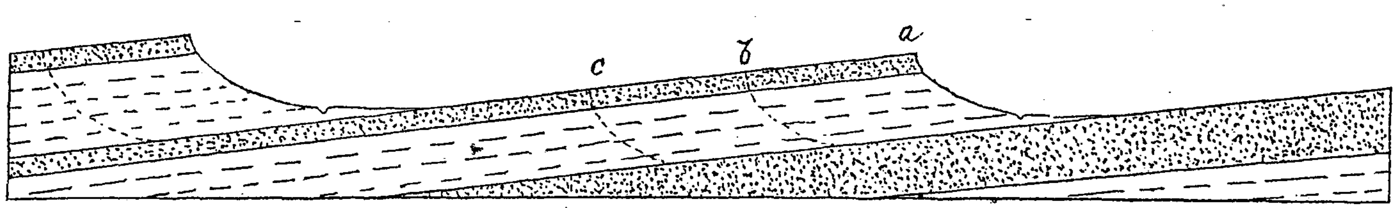


FIG. 69.—Ideal cross-section of inclined strata, to show the Shifting of Divides in Cliff Erosion. Successive positions of a divide are indicated at *a*, *b*, and *c*.

Fig. 20 B

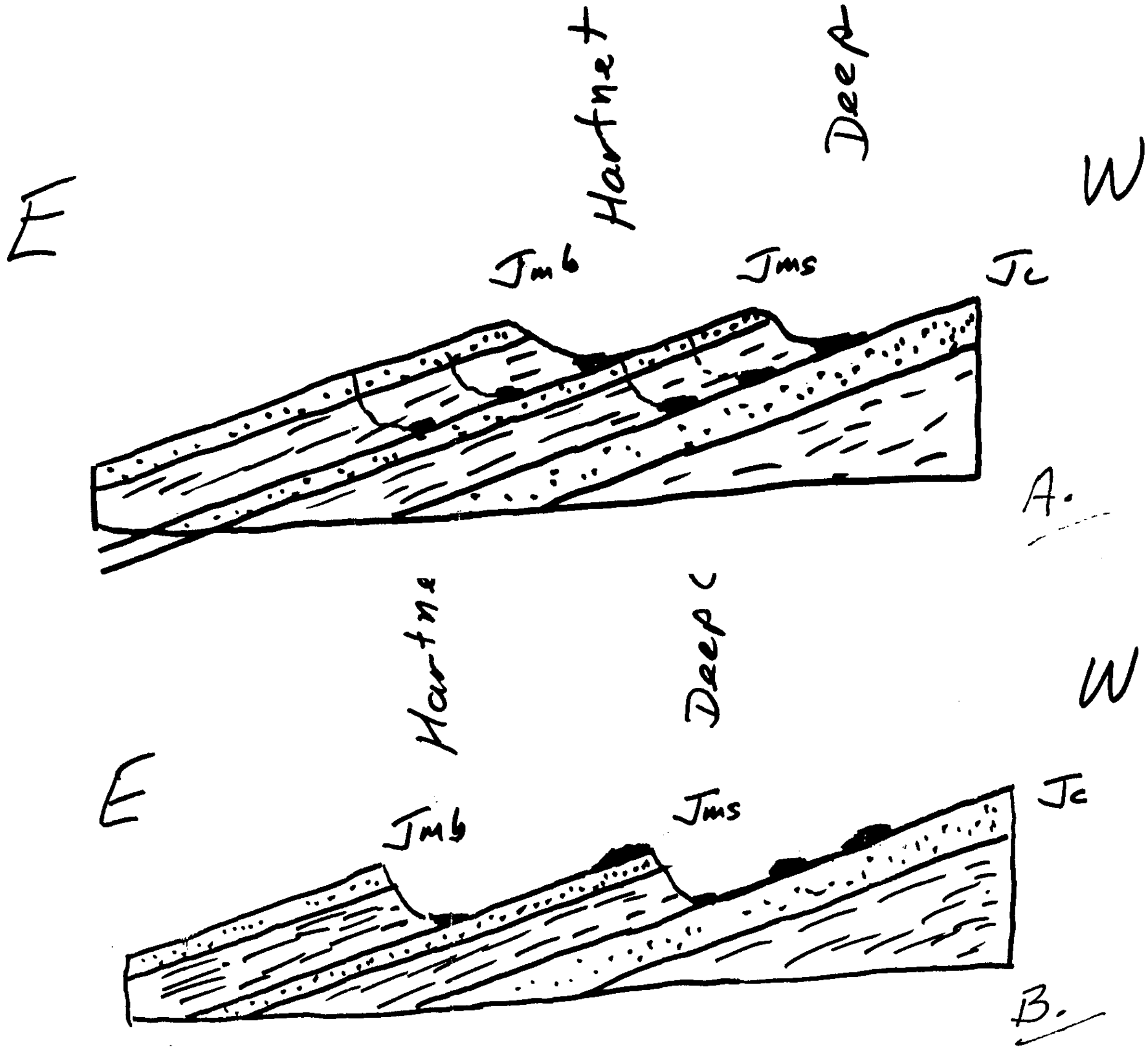

Hartnet
Deep
E
W
Jmb
Jms
Jc
A.
Hartne
Deep C
W
E
Jmb
Jms
Jc
B.

Fig. 21

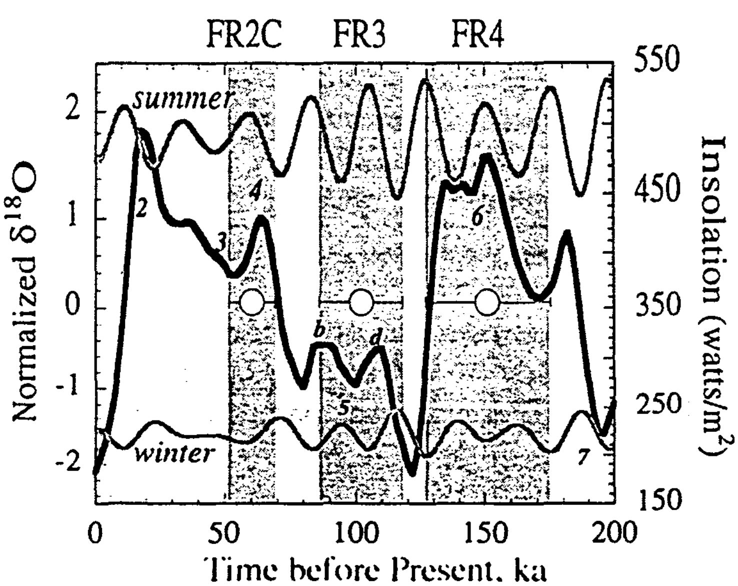

FR2C
FR3
FR4
summer
winter
Normalized $\delta^{18}O$
Insolation (watts/m^2)
Time before Present, ka
0
50
100
150
200
2
1
0
-1
-2
550
450
350
250
150
2
3
4
5
6
7
b
d

Fig. 22