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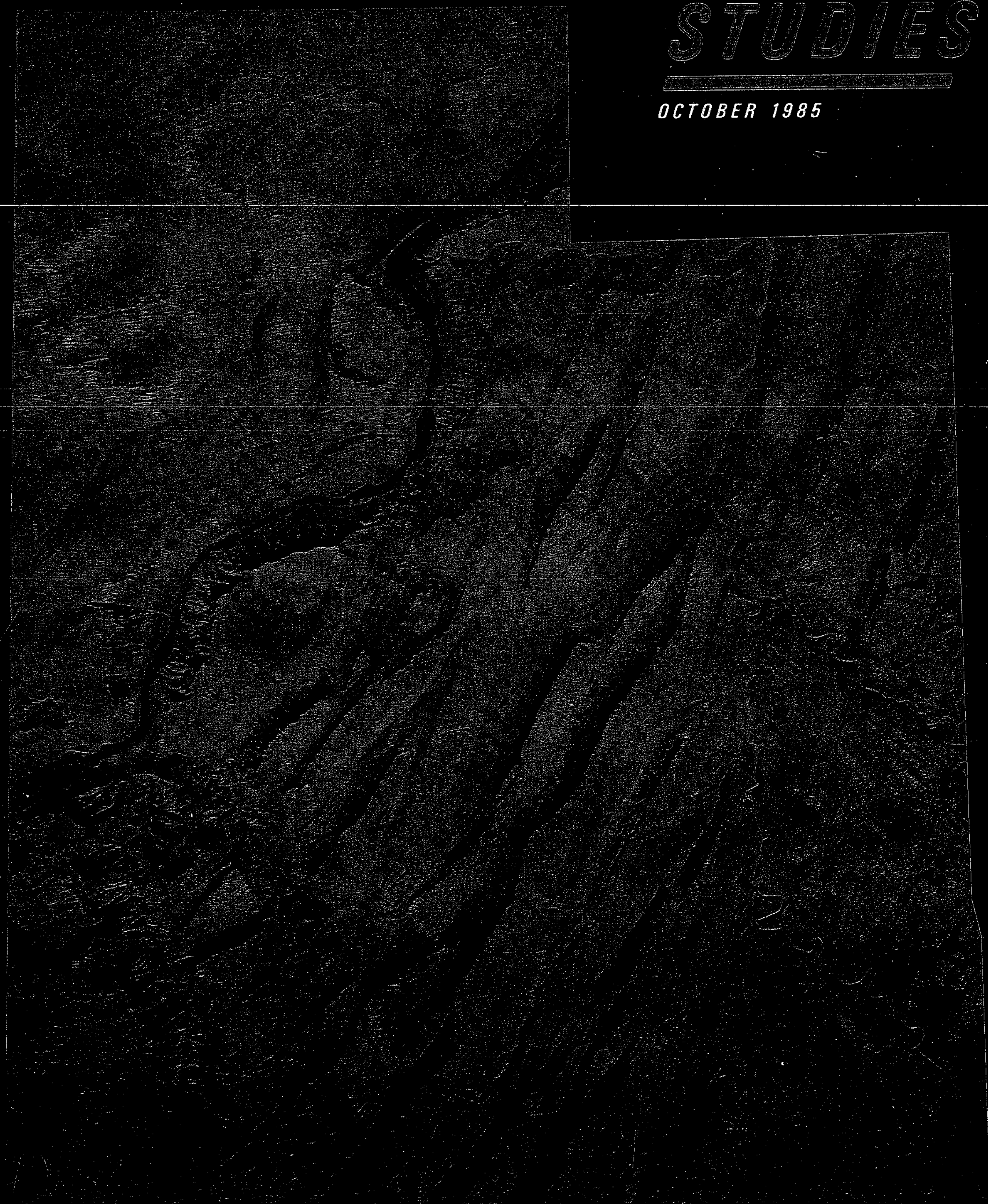

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Late Cenozoic Geology of the Beaver Basin, Southwestern Utah

MICHAEL N. MACHETTE
U.S. Geological Survey, P.O. Box 25046, Denver Federal Center, Denver, Colorado 80225

ABSTRACT

The Beaver Basin contains nearly 1,500 m of upper Cenozoic sedimentary rocks that record nearly continuous middle(?) Miocene to early Pleistocene closed-basin deposition in alluvial-fan, piedmont-slope, floodplain, and lacustrine environments. The upper parts of this sequence are Pliocene to early Pleistocene and contain at least six different beds of tephra (volcanic ash) and an early Pleistocene (1.1 m.y.) basaltic lava. Most of the tephra are preserved as water-laid ash beds in the upper Pliocene lacustrine sediments of ancient Lake Beaver.

About 750,000 years ago, Lake Beaver was drained by the opening of an outlet at the southwest corner of the basin. About 500,000 years ago, the gravel of Last Chance Bench was deposited on a broad pediment surface cut across most of the basin. Since then, sedimentation in open-basin conditions has resulted in a mainly erosional sequence of climatically controlled alluvium that forms terrace and piedmont-slope landforms graded to progressively lower local baselevels along the Beaver River and its tributaries.

Age control for the basin deposits is provided by potassium-argon age determinations and tephrochronologic studies of the volcanic units, preliminary uranium-trend ages on the younger alluvial units, and estimates of soil age. Soil ages are based on developmental characteristics such as the clay content and color of B horizons, and on the amount and rate of accumulation of secondary calcium carbonate ($CaCO_3$) in Pleistocene calcic soils and calcretes. Over the past 500,000 years, the calcic soils that have formed in gravel of Last Chance Bench have accumulated 0.14 ± 0.01 g of $CaCO_3$ per square centimeter of soil column every 1,000 years.

The closed-basin deposits and the younger open-basin sediments are uplifted in a horst near the north end of the basin and deformed into a broad south-plunging antiform in the central part of the basin. Both groups of deposits are displaced by basin-margin faults that form a 4-km-wide zone at the base of the Tushar Mountains. Detailed mapping of the displaced Pleistocene alluvium and data on the morphology of the resulting fault scarps suggest that many of the faults have moved as recently as late Pleistocene or early Holocene. Both in style and location, the Pliocene and Pleistocene deformation seems to be a continuation of Miocene deformation; therefore, the structures exposed in the younger sediments may be a useful guide for further exploration of oil, gas, and uranium in the Beaver Basin.

INTRODUCTION

The Beaver Basin of southwestern Utah is a topographic and structural depression that has been the site of extensive deposition and deformation since late Miocene time. The basin is about 25 km long north-to-south and 16 to 22 km wide; it lies astride the transitional zone between the eastern Basin and Range and western Colorado Plateau Provinces (fig. 1). On the east it is bordered by upper Oligocene to lower Miocene volcanic rocks (Cunningham and others 1983) of the Tushar Mountains (fig. 2). Gently north-dipping Miocene volcanic rocks of the northeastern Black Mountains crop out along the irregular southern margin of the basin. On the west it is rimmed by Tertiary granite and older rocks of the spectacular Mineral Mountains, Utah's largest exposed pluton (Sibbett and Nielson 1980). Low hills along the northern border of the basin that lie on east-tilted Tertiary volcanic rocks and metamorphosed Paleozoic rocks (Steven and Morris 1983; Machette and Steven 1983) are 9-m.y. rhyolite of Gillies Hill (Evans and Steven 1982).

The mountain ranges adjacent to the Beaver Basin were uplifted during the Miocene to Pleistocene along north-northeast-trending normal faults; this uplift coupled with regional extension formed a deep basin that is now filled with as much as 2,000 m of sedimentary rock. This area was the site of prolonged closed-basin deposition during Miocene through early(?) Pleistocene time; there was no significant sediment outlet from the basin. With the formation of an outlet at the southwest corner of the Beaver Basin about 750,000 years ago, open-basin deposition took place for the remainder of the Quaternary. Subsequent Pleistocene to Holocene erosional and depositional events are recorded by alluvial sediments that probably reflect climatic, rather than tectonic control. Accelerated stream erosion related to lowering of baselevel through the outlet and extensive faulting in the center of the basin exposed a nearly continuous section of Pliocene to lower Pleistocene sedimentary rocks and middle Pleistocene to Holocene alluvium. These rocks contain as many as six Pliocene to middle Pleistocene tephra that were erupted from rhyolites of local vents and distant calderas in the western United States.

INITIAL DEVELOPMENT OF THE BEAVER BASIN

Evidence of the initial (Miocene?) development of the Beaver Basin is scant because basin-fill deposits of this age are rarely exposed. However, Evans and Steven (1982) found Miocene sediment just southwest of Cove Fort, Utah (fig. 2), that are probably continuous with buried units in the Beaver Basin. Cook and others (1980) suggested that a north–south-trending gravity low between the Woodtick Hill–Gillies Hill area and the Tushar Mountains is caused by thick basin-fill sediment below and east of the rhyolite. They refer to this low-gravity area and its extension to the north and south as the Beaver–Cove Fort graben. Unfortunately, little information can be determined about the thickness or the configuration of the Miocene basin.

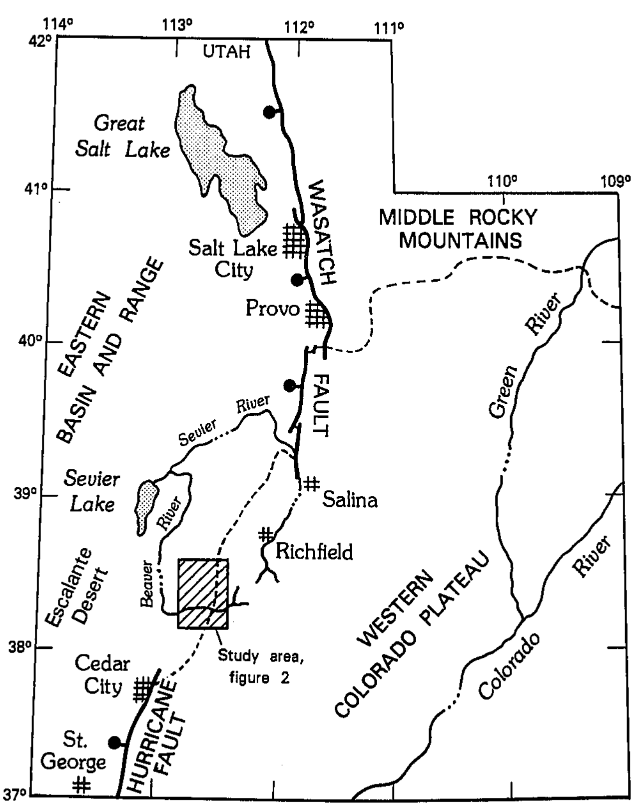


FIGURE 1.—*Index map of the Beaver Basin, southwestern Utah. Bar and ball on downthrown sides of faults.*

The Beaver and Cove Fort Basins are separated by a major topographic divide. Although the divide is now structurally and topographically high, there is no substantive evidence that it existed before the eruption of the 9-m.y. rhyolite of Gillies Hill. The rhyolite lies on east-tilted, pre-22-m.y. volcanic rocks erupted from sources in the Tushar Mountains (Steven and Morris 1983). The lateral extent of these older volcanic rocks shows that this area was not elevated relative to the Tushar area in early Miocene time. However, collapse of the Beaver–Cove Fort graben between the Mineral and Tushar Mountains must have occurred prior to 9 m.y. ago. Cuttings from the Badger Lu-Lu #1 well (fig. 2) show that the central part of the Beaver Basin has about 1,500 m of Miocene and Pliocene closed-basin sedimentary rocks that lie on an additional 1,300 m of lower Miocene to Oligocene volcanic rocks. Thus, from subsurface data and the lateral extent of the volcanic rocks, a thick section of pre-9-m.y. sedimentary rocks may lie within the Beaver–Cove Fort graben as Cook and others (1980) suggested.

If this interpretation is correct, then the Cove Fort and Beaver Basins must have been connected during the Miocene, and probably were structurally depressed relative to the Tushar and Mineral Mountains by middle Miocene time. Most of the present structural relief at the northern end of the Beaver Basin (the divide area) is a result of post-9-m.y. uplift of the Maple Flats horst, whereas much of the divide's present topographic relief is a result of the eruption of the rhyolite of Gillies Hill 9 m.y. ago.

Evidence of late Miocene deposition is preserved beneath a basalt that forms the abutments of Minersville Reservoir in the southwest corner of the Beaver Basin. Here, a 7.6-m.y. basalt flow (Best and others 1980) lies on channel-filling conglomerate that contains pumice. The pumice was erupted from 8–9-m.y. rhyolite that crops out southeast of the reservoir and in the Gillies Hill area at the north end of the basin (Evans and Steven 1982). Imbricated pebbles and cobbles in the conglomerate suggest that, at least for a short period of time, sediment from the Beaver Basin was transported westward to the Escalante Desert, ultimately to a baselevel 250 m lower. The basin was later reclosed by uplift along the southeastern flank of the Mineral Mountains and along the northern flank of the Black Mountains (fig. 2), as indicated by as much as 20° of tilting of the overlying basalt. It remained closed until about 750,000 years ago when headward deepening of Minersville Canyon through the southern Mineral

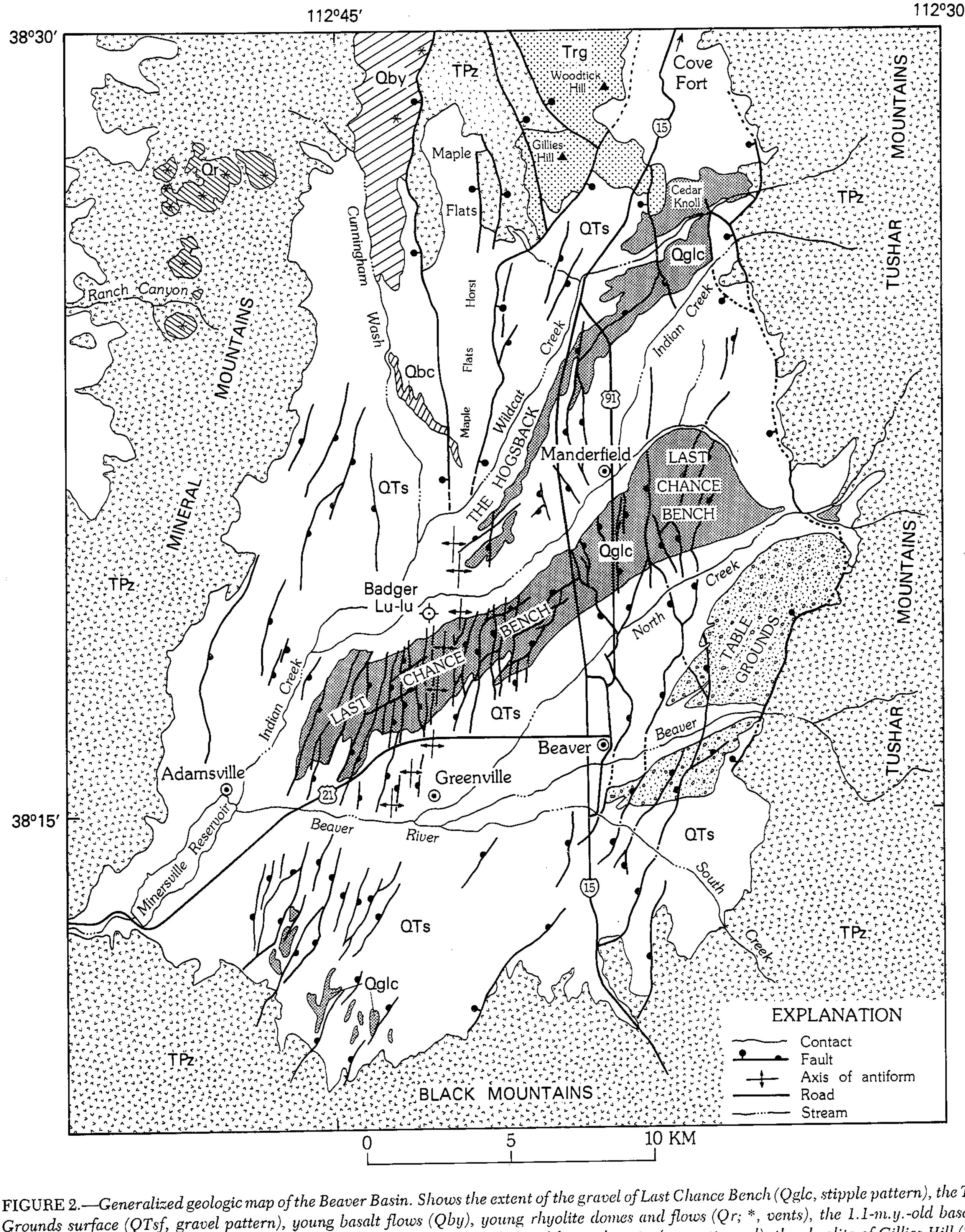


FIGURE 2.—*Generalized geologic map of the Beaver Basin. Shows the extent of the gravel of Last Chance Bench (Qglc, stipple pattern), the Table Grounds surface (QTsf, gravel pattern), young basalt flows (Qby), young rhyolite domes and flows (Qr; *, vents), the 1.1-m.y.-old basalt of Cunningham Hill (Qbc), undivided Quaternary and Tertiary open- and closed-basin deposits (not patterned), the rhyolite of Gillies Hill (Trg), undivided Tertiary (Tv) to Paleozoic (TPz) bedrock, the Last Chance Bench antiform, and major faults. Many more faults are present than are shown. (Bar and bell indicate downdropped side of basin-margin faults; semicircle indicates downdropped side of intrabasin-faults in middle Pleistocene and younger alluvium.)*

Range allowed the Beaver River to again flow west.

A wide zone of normal faults along the eastern side of the Beaver Basin (fig. 2) marks the modern transition between the Colorado Plateau Province (including the Tushar Mountains) and the Basin and Range Province (including the Mineral Mountains). The faults having the greatest displacement lie within the basin fill adjacent to the mountain front, rather than directly at the mountain front. For example, the surface of 21–23-m.y. mafic lavas are offset only 150 m across the conspicuous frontal fault of the Tushar Mountains (fig. 2). The faults 1–4 km west of the Tushars have a cumulative post-early Miocene stratigraphic throw of several kilometers, yet their individual displacements since the early Pleistocene are only 10–100 m. This suggests that the topographic expression of the Tushar Range and, by similar evidence and reasoning, the Mineral Range, is largely a product of uplift during the Pliocene and Miocene.

BASIN STRATIGRAPHY

The Beaver Basin contains 1,500–2,000 m of sedimentary rocks that were deposited during the Miocene to early Pleistocene in a closed basin and several hundred meters of middle Pleistocene to Holocene sediments that were deposited in an open basin (fig. 3). The closed-basin rocks are divided into an upper and lower part on the basis of degree of oxidation and cementation, environment of deposition, and age.

Most of the exposed fill in the Beaver Basin consists of upper Pliocene to middle Pleistocene closed-basin sediment that is covered locally by a thin mantle of middle Pleistocene to Holocene alluvium. However, upper(?) Miocene conglomerate is exposed in the south-trending Maple Flats horst in the north central part of the basin (fig. 2). This horst exposes the largest area of lower closed-basin deposits.

In 1981, a wildcat exploratory well (Badger Lu-Lu #1) was spudded in upper Pliocene sediment about 1.5 km west of the surficial axis of the south-plunging Last Chance Bench antiform. Cuttings from the well indicate that it penetrated 1,360 m of Miocene and Pliocene closed-basin sedimentary rocks and about 1,260 m of lower Miocene to upper Oligocene volcanic rocks. Unpublished seismic-reflection data (Lamar Rohmer, Badger Oil Co., oral communication 1981) from an east–west line that crosses near the drilling site show that the basin-fill deposits thicken considerably toward the eastern (in particular) and western margins of the basin. From these data and the distribution of closed-basin sediment, it appears that the east and south central parts of the Beaver Basin are the deepest and contain perhaps as much as 2,000 m of closed-basin sediment. This interpretation is supported by a preliminary compilation of regional gravity data (D. L. Campbell written communication 1983).

LOWER CLOSED-BASIN DEPOSITS

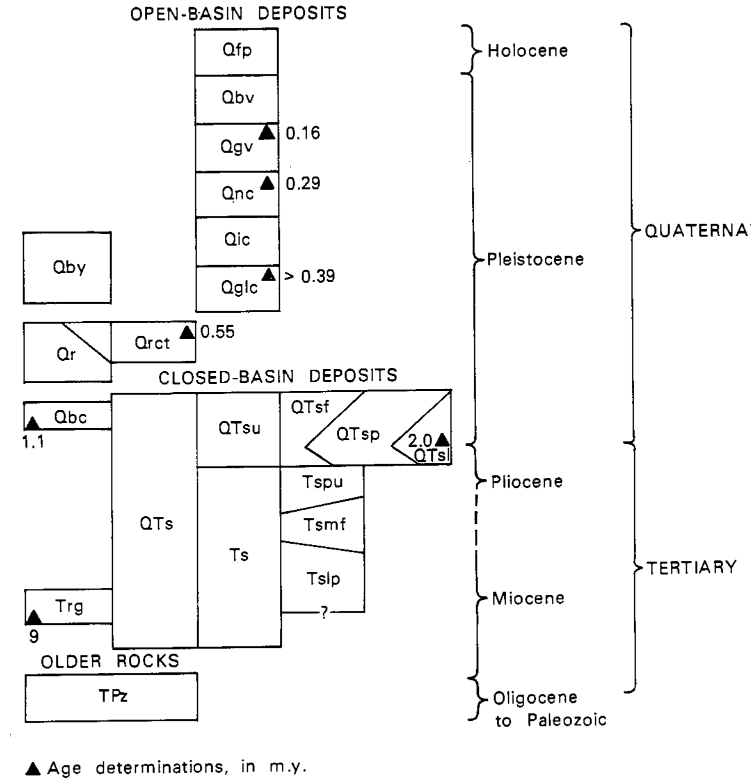
The lower closed-basin deposits are divided into three informal units or members, and the rhyolite of Gillies Hill (fig. 3; units Tspu, Tspf, Tspl, and Trg). These rocks are best exposed in a south-plunging antiform beneath conglomerate at the south end of Maple Flats horst (Machette and Steven 1983). The lowest and most poorly exposed of these deposits is named the lower piedmont unit (Tspl). In the north central part of the basin it consists of moderately oxidized, slightly gypsiferous, fine-grained bolson sediment of unknown thickness. The upper Miocene pumice-bearing conglomerate near Minersville Reservoir probably is a coarse-grained channel facies within the lower piedmont unit. Cuttings from the Badger well indicate that the lower piedmont unit coarsens downward and may be as much as 500 m thick below the central part of the basin. In the southern part of the basin, a suspected west-trending normal fault just south of the Beaver River may have uplifted the lower piedmont unit to within several hundred meters of the surface. If such a fault exists, the overlying Pliocene to middle Pleistocene sediments are markedly thinner south of the Beaver River than in most other parts of the basin.

The lower piedmont unit is overlain by coarse-grained, oxidized, calcareous sandstone and sandy pebble conglomerate with interbedded siltstone and claystone; these rocks are collectively named the Conglomerate of Maple Flats (Tsmf; Machette and Steven 1983). The conglomerate is probably late Miocene to early Pliocene in age; it lies on and contains clasts derived from the rhyolite of Gillies Hill (9 m.y.). Boulders of limestone and granite as much as 2 m in diameter in the conglomerate reflect uplift of the Mineral Range and possibly of the Tushar Mountains along basin-margin faults.

At least 250 m of the conglomerate is exposed at the south end of Maple Flats. On the basis of cuttings from the Badger well, which was drilled about 4 km south of the southernmost exposure of the conglomerate, it appears that the conglomerate is at least 500 m thick in the subsurface. In the southern part of the basin, it may be considerably thinner than 500 m, owing to lesser amounts of uplift along the south margin of the basin.

The youngest of the lower closed-basin deposits is the upper piedmont unit (Tspu), which consists of interbedded stream-channel and deltaic(?) sand and pebble to cobble gravel and calcareous marl. It is moderately oxidized and indurated and contains lenses of calcium-carbonate-cemented sandstones and nodules of calcium carbonate. In the north central part of the basin, this unit is a distal-piedmont facies that probably grades basinward

EXPLANATION
(OF FIGURES 2, 4, 5, and 6)
CORRELATION OF UNITS



OPEN-BASIN DEPOSITS (HOLOCENE TO MIDDLE PLEISTOCENE)—Consists of terrace, piedmont-slope, alluvial-fan, and floodplain alluvium. Deposits are mainly remnants of stream downcutting associated with the establishment of a drainage outlet from the Beaver Basin westward to the Escalante Desert

Qfp Floodplain alluvium (Holocene, $<$10,000 yr B.P.)

Qbv Alluvium of Beaver (12,000–15,000 yr B.P.)

Qgv Alluvium of Greenville (140,000 yr B.P.)

Qnc Alluvium of North Creek (250,000 yr B.P.)

Qic Gravel of Indian Creek (350,000–400,000 yr B.P.)

Qby Basalts of Red Knoll and Crater Knoll (middle? Pleistocene)—Flows and cones

Qglc Gravel of Last Chance Bench (500,000 yr B.P.)—Thin mantle of gravel lies on erosional pediment cut across older deposits

Qrct Tephra of Ranch Canyon (550,000 yr B.P.)—Water-laid pumice

Qr Rhyolite domes and flows (Middle to lower? Pleistocene)—Source of tephra of Ranch Canyon

QTs CLOSED-BASIN DEPOSITS (LOWER PLEISTOCENE TO UPPER? MIOCENE)—Includes informal units of poorly to moderately consolidated fluvial and lacustrine sediment divided into two packages

QTsu Upper closed-basin sediment (lower? Pleistocene to upper Pliocene)—Gradational sequence of lacustrine (QTsl), piedmont-slope and fluvial (QTsp), and fanglomeratic (QTsf) sediment. Contains beds of the Last Chance Bench ash (1.6? m.y.), the Huckleberry Ridge ash (2.0 m.y.), the middle ash (2.1 m.y.), and the Indian Creek and The Hogsback ashes (2.3—2.4 m.y.). Also includes the basalt of Cunningham Hill (Qbc; 1.1 ± 0.3 m.y. B.P.) in upper part of section

Ts Lower closed-basin sediment (upper Pliocene to upper? Miocene)—Vertical sequence of moderately oxidized (in surface exposure), calcareous, indurated sediments. Upper-piedmont (Tspu) and lower-piedmont (Tspl) units are relatively fine-grained and are separated by the Conglomerate of Maple Flats (Tsmf)

Trg Rhyolite and rhyolite tuff of Gillies Hill (9 m.y. B.P.)

TPz OLDER ROCKS (MIOCENE TO PALEOZOIC)—Volcanic, sedimentary, metamorphic, and intrusive rocks surrounding the Beaver Basin

FIGURE 3.—*Correlation and brief description of major upper Cenozoic units in the Beaver Basin shown on figures 2, 4, 5, and 6.*

into a playa or lacustrine facies, and mountainward into a coarse-grained alluvial-fan facies. Several water-laid tephra beds occur in the upper part of this unit, but their sources and ages have not been determined. The upper piedmont unit is distinguished from younger and older closed-basin sediment by its moderate amount of oxidation, its calcareous marls, and its tephra assemblage.

The lower and thicker part of the closed-basin deposits is thus subdivided into upper and lower piedmont units and the intervening Conglomerate of Maple Flats (Tsmf). These units are overlain conformably and unconformably by the upper part of the closed-basin deposits, which are widely exposed and have abundant, dated marker beds (fig. 4).

UPPER CLOSED-BASIN DEPOSITS

The upper closed-basin deposits consist of laterally intertonguing alluvial-fan, stream, piedmont-slope, and lacustrine sediments that were deposited during late(?) Pliocene to early(?) Pleistocene time in and adjacent to a large perennial lake, here informally named Lake Beaver.

FANGLOMERATE FACIES

The fanglomerate facies (fig. 3, QTsf) is the coarsest part of the upper closed-basin deposits. It consists of poorly indurated boulder and sandy pebble gravel, moderate to well-rounded, that grade basinward into the piedmont facies. The fanglomerates were deposited as

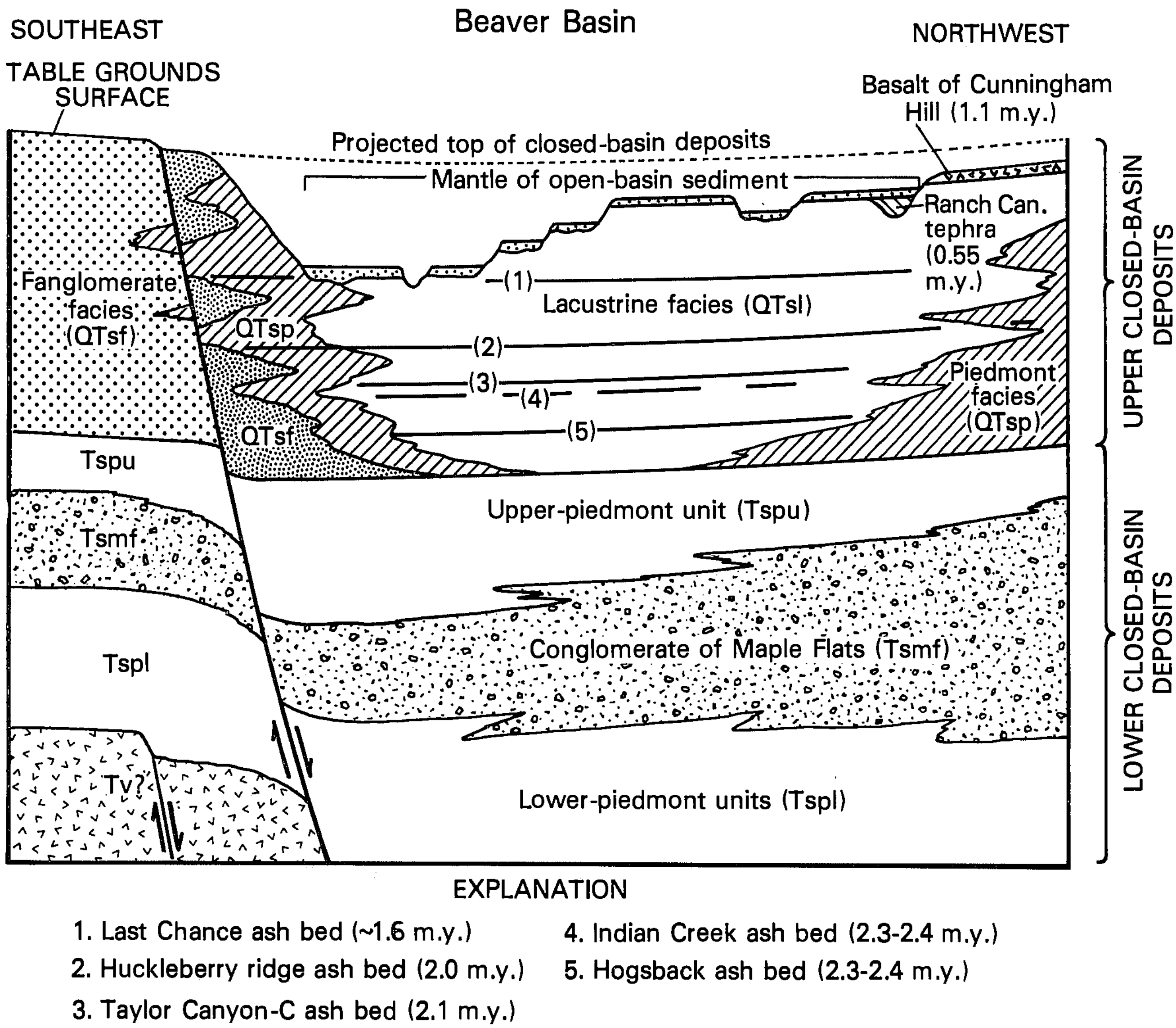


FIGURE 4.—*Stratigraphic diagram across the Beaver Basin showing relations between the upper and lower closed-basin rocks of the Beaver Basin. Also shows stratigraphic position of basalt flow and beds of tephra (volcanic ash and pumice). Bar and ball on downthrown side of faults. See figure 3 for letter symbols.*

alluvial fans that flanked the mountain ranges and, to a lesser extent, as stream floodplains. Although present around the entire basin, they are thickest along the eastern side and are best exposed in a large gravel pit at the eroded, western edge of the Table Grounds surface (fig. 2). Here the Table Grounds is underlain by more than 100 m of coarse-grained, slightly oxidized sandy gravels containing subangular pebbles and cobbles with sparse interbeds of sand.

Table Grounds is the constructional surface formed by the youngest part of the fanglomerate facies. The Table Grounds surface forms a broad fan-shaped apron that laps onto the western front of the Tushar Mountains. It lies 45–75 m above North Creek and 75–100 m above the Beaver River. The southernmost remnant of the Table Grounds surface forms an elongate ridge just south of the Beaver River. Throughout most of the basin, the early Pleistocene closed-basin deposits that underlie the Table Grounds surface are either buried by younger open-basin sediment or have been eroded due to progressive lowering of local baselevel since the early Pleistocene.

The Table Grounds surface is about 0.75 m.y. old, based on rates of sedimentation of the upper closed-basin sediments, the 1.1-m.y. age of the basalt of Cunningham Hill (Qbc; Best and others 1980), the 0.55-m.y. age of the tephra of Ranch Canyon (Izett 1981, p. 10215), and an estimate of the age of the soil formed below the Table Grounds surface (Machette 1982).

PIEDMONT FACIES

The piedmont facies (fig. 3, QTsp) is an interfingering gradation of the coarse-grained, range-bounding fanglomerate facies and the fine-grained, basin-center lacustrine facies. The piedmont facies was deposited in distal coalesced alluvial-fan, stream-delta, and playa (or lake) environments. It crops out in a 4- to 6-km-wide band in the central and northern parts of the basin (Machette and others 1983), but is best exposed along the eroded northern edge of Last Chance Bench. Here the piedmont facies consists of well-bedded, sandy, pebble- to cobble-size gravel with abundant secondary manganese coatings. Basinward, the piedmont-facies is coarse- to fine-grained sands that interfinger with silts, clays, and fine-grained sand of the lacustrine facies.

LACUSTRINE FACIES

The lacustrine facies (fig. 3, QTsl) is the fine-grained end-member of the upper closed-basin sediment and, as such, it is the most widespread and best exposed of the facies and provides a nearly continuous 1-m.y.-long record of deposition in Lake Beaver. The lacustrine facies consists of light to medium green silty clay and silt and well-bedded, light gray to light brown fine-grained sand that grades mountainward into pebbly sands of the piedmont facies. Ripple-marked sandstones and mudcracked claystones show that Lake Beaver was shallow and occasionally dry. About 200–250 m of lacustrine facies is exposed in the north central part of the basin, but cuttings from the Badger well and numerous exploratory holes for uranium show that the lacustrine facies is thicker in the subsurface, especially in the south central part of the basin near Greenville (fig. 4).

Stratigraphic Marker Beds

The upper closed-basin deposits contain a well-preserved sequence of ash beds (tephra), fossils, and a local basalt flow, which provide dated stratigraphic markers. At least five ash beds accumulated in Lake Beaver during the late Pliocene and early Pleistocene (fig. 4); some of these beds were erupted from local vents, whereas others were erupted from calderas thousands of kilometers away. Tephra is best preserved in the lacustrine facies either as airfall or as water-laid material that was reconcentrated from adjacent slopes. However, a few outcrops of reworked ash are preserved in channels in the piedmont (QTsp) and fanglomerate (QTsf) facies of the upper closed-basin sedimentary rocks. Additional ash beds crop out in lower(?) Pliocene to Miocene rocks, but these are not discussed here because little is known about their distribution, age, and source areas.

The five ash beds are contained within the basal 70–75 m of the upper closed-basin sediment. This part of the section probably ranges from 2.4 to 1.6 m.y., a time interval that transgresses the Pliocene-Pleistocene boundary as determined from many recent studies. In the Beaver Basin the most widespread ash bed is 2.0 m.y. old; therefore, I use 2.0 m.y. as a convenient boundary for the Pliocene and Pleistocene.

TEPHRA

The Hogsback ash bed (Izett 1981, p. 10218) is the stratigraphically lowest traceable ash bed in the sequence. Where locally exposed along the north side of The Hogsback surface (fig. 2), the ash is white to light gray, glassy, and forms a 5- to 10-cm-thick bed about 50 m below the Huckleberry Ridge ash bed (the fourth of five beds). The Hogsback ash has chemical and mineralogical affinities with 2.3- to 2.4-m.y.-old rhyolites exposed in the Cudahy Mine and at South Twin Peak (Izett 1981, plate 1), two vents exposed 55 km northwest of Beaver, Utah.

The second and third ash beds in this sequence are widely preserved in the 30 m of sediment underlying the Huckleberry Ridge ash bed (fig. 4). Both ash beds are in light green silty clay and slightly oxidized orange-brown sand of the lacustrine facies.

The Indian Creek (second) ash bed (Izett 1981, p. 10218) is 4 m below the third ash bed and about 30 m below the Huckleberry Ridge ash bed. Indian Creek ash is significantly coarser grained than the other four ashes; it has glassy, gray to black granules in a medium-grained, glassy, fine-sand-sized matrix. The relatively coarse texture of the ash suggests that the source was nearby, perhaps less than 100 km away. The ash is similar to The Hogsback ash in that it has chemical and mineralogical affinities with 2.3–2.4-m.y. rhyolites exposed at the Cudahy Mine and at South Twin Peak (Lipman and others 1978, table 3; Izett 1981, plate 1). The third ash bed is correlated with the 2.1-m.y. Taylor Canyon-C ash bed on the basis of stratigraphic position and chemical and mineralogical affinities with the rhyolite of Taylor Canyon near Glass Mountain in eastern California (Izett 1981, p. 10218).

The Huckleberry Ridge ash bed (Izett 1981, p. 10218) is the most widespread of the ash beds; about 50 exposures of water-laid Huckleberry Ridge ash occur in the west and south two-thirds of the Beaver Basin. It lies 12–15 m below a diagnostic, local medium- to coarse-grained, ripple-bedded sandstone that is exposed along the north central edge of Last Chance Bench. The ash was erupted from a caldera in the Yellowstone Park area of northwestern Wyoming about 2.0 m.y. ago (Izett 1981, 1982; Izett and Wilcox 1982). The basal part of the bed is composed of 5–10 cm of clean, coarse-grained, water-laid airfall ash, whereas the upper part has 80–150 cm of reworked, fine-grained ash that has spectacular sedimentary and load structures. Its lateral extent shows that Lake Beaver occupied a major portion of the basin during the latest Pliocene and earliest Pleistocene, about 2.0 m.y. ago.

The fifth and youngest tephra is a 5-cm-thick layer of white, fine-grained ash, informally named the Last Chance Bench ash bed (Izett 1981, pp. 10217–18). It is exposed about 15–25 m below the north edge of the Last Chance Bench surface, slightly west of the axis of the Last Chance Bench antiform (figs. 2 and 5). Izett (written communication 1983) considers the ash to be about 1.6 m.y. old on the basis of its stratigraphic position with respect to dated ash beds (32–40 m above the Huckleberry Ridge) and its chemical and mineralogic similarities with lower Pleistocene Bishop-type ashes from the Glass Mountain–Long Valley area of eastern California (Izett 1981, plate 1).

BASALT OF CUNNINGHAM HILL

The basalt of Cunningham Hill (fig. 2, Qbc) is the youngest dated rock in the upper part of the closed-basin deposits (Machette and Steven 1983). This dark gray, scoriaceous to massive lava fills an ancient stream channel of Cunningham Wash. Although the vent for the basalt of Cunningham Hill is no longer exposed, it must be concealed to the north beneath younger basalts (fig. 2, Qby) and alluvium in a narrow graben formed by the east-bounding fault of the Mineral Range and the west-bounding fault of the Maple Flats horst. The age of the basalt, as determined by potassium-argon methods, is 1.1 ± 0.3 m.y. (Best and others 1980). The basalt has a strong normal magnetic direction; however, after 300 Oerstead AC demagnetization, the basalt was weakly reversed. These data suggest that the normal direction is a chemical overprint. In accord with the K-Ar age of the basalt, the magnetic data suggest that the basalt must be older than 0.73 m.y., which is the minimum age of the youngest, significantly long reversed paleomagnetic epoch, 0.73–0.90 m.y. ago (time scale of Mankinen and Dalrymple 1979).

The basalt of Cunningham Hill flowed in a south- to southeast-trending paleostream channel toward the central part of the Beaver Basin. This flow direction indicates that the basin was not opened (integrated to the west) prior to basalt extrusion. However, in this same area, middle Pleistocene and younger open-basin alluvium lie in channels that flow south and southwest toward the basin's outlet. Because of tilting along north–south normal faults, the basalt now forms a broken ridge about 100 m above the present stream level in the north part of the basin.

PALEONTOLOGY AND PALEOENVIRONMENTAL IMPLICATIONS

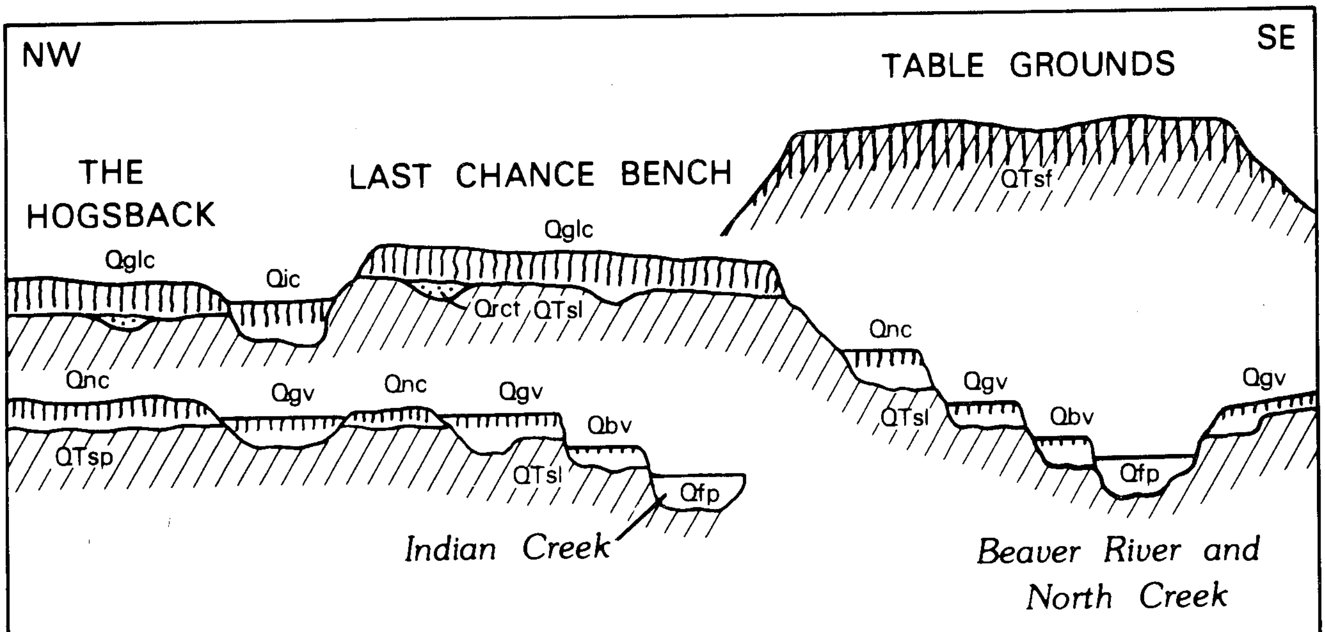
The lacustrine sequence has an excellent assemblage of both small and large vertebrate fossils, gastropods, and plant fossils such as *Scirpus* (a sedge of the bulrush family) and *Chara* (a grass green algae). In addition, ripple marks and sparse mudcracks are found in some of the sandstones, suggesting that Lake Beaver was a shallow, permanent lake. Occasionally it may have been a playa, probably owing to changes in water budget and evaporation. A general lack of carbonate mineralization in the upper part of the closed-basin sediment indicates that the water was not saturated with Ca^{++}, whereas carbonate cementation is common in the older, lower part of the section.

Ostracodes and diatoms in the upper closed-basin sediment were collected by R. M. Forester and J. P. Bradbury, respectively, from a 35-m-thick section under the Huckleberry Ridge ash bed and from a 12-m-thick section that contains the Last Chance Bench ash bed. Spot collections also were made from the lower closed-basin sediment. Forester and Bradbury (1981) suggest that the Beaver Basin had at least four distinctive lacustrine systems and varying marginal environments during Pliocene and early Pleistocene time. These lacustrine systems include (1) a Pliocene freshwater lake (deltaic part of piedmont facies), (2) a late Pliocene saline lake (basal lacustrine facies), (3) a late Pliocene to early Pleistocene slightly saline to freshwater lake (middle? lacustrine facies), and (4) an early Pleistocene freshwater lake-pond-stream network (upper? lacustrine facies) similar to some of the modern-day environments of the basin. (For additional information on water chemistry and paleoecology see Forester and Bradbury 1981).

TIMING OF BASIN OPENING

Closed-basin deposition continued well into the early Pleistocene as shown by the depositional pattern of the basalt of Cunningham Hill, but by middle Pleistocene time Lake Beaver was breached by overtopping and erosion or by headward stream incision in Minersville Canyon. This breach opened the basin and integrated its drainage system with that of the Escalante Desert to the west of the Mineral Range. The result was a dramatic 250-m lowering of baselevel followed by a period of extensive lateral planation (pediment formation) prior to and during deposition of the gravel of Last Chance Bench. For the remainder of the Quaternary, open-basin sediment was periodically deposited in response to climatically(?) induced changes in sediment load and stream discharge.

The time at which the basin was opened is bracketed by ages from the youngest dated unit in the upper closed-basin sediment (the basalt of Cunningham Hill, 1.1 m.y.) and the oldest dated unit in the open-basin sediment (the tephra of Ranch Canyon, 0.55 m.y.). These age brackets can be further narrowed using estimates of the age of the



SYMBOL	GEOLOGIC UNIT	AGE, IN YEARS BEFORE PRESENT
Qfp	Holocene alluvium	Holocene (less than 10,000)
Qbv	Alluvium of Beaver	Latest Pleistocene (12,000–15,000)
Qgv	Alluvium of Greenville	Late Pleistocene (140,000)
Qnc	Alluvium of North Creek	Middle Pleistocene (250,000)
Qic	Gravel of Indian Creek	Middle Pleistocene (350,000–400,000)
Qglc	Gravel of Last Chance Bench	Middle Pleistocene (500,000)
Qrct	Tephra of Ranch Canyon	Middle Pleistocene (550,000)
QTsu	Upper closed-basin deposits	Early Pleistocene (750,000–2 m.y.) and Pliocene (2–5 m.y.)
QTsf	Fanglomerate facies	
QTsp	Piedmont-slope facies	
QTsl	Lacustrine facies	
╥╥╥╥	Soils in alluvium	Pattern proportional to depth and degree of soil development

FIGURE 5.—*Schematic diagram showing the topographic and relative stratigraphic position of the open-basin sediments, Last Chance Bench, and Table Grounds (top of the closed-basin sediment, QTsf).*

Table Grounds surface, which is the constructional top of the closed-basin sediment. The age of this surface is considered to be about 750,000 years on the basis of soil morphology, thickness, and carbonate content (see discussion in soils section).

OPEN-BASIN SEDIMENTS

Open-basin sediments in the Beaver Basin record episodic deposition during the past 550,000 years. Most of these sediments were deposited by the Beaver River and its tributaries after they were integrated into the Escalante River drainage system to the west. The sediments include alluvial-fan, piedmont-slope, terrace, and floodplain alluvium as well as colluvium, landslide debris, and the tephra of Ranch Canyon (fig. 3). The open-basin sediments are informally named for local geographic features or towns near where they are best exposed or preserved. This usage is indicated by lowercase terms; for example, the gravel of Last Chance Bench underlies Last Chance Bench, a major physiographic surface in the basin.

The open-basin sediments form three distinct landforms: terraces, piedmont slopes, and alluvial fans (Machette 1983; Machette and Steven 1983; Machette and others 1983). Field relations indicate that the alluvium of alluvial fans and piedmont slopes interfingers with and overlaps coeval terrace alluvium. Because this same relation occurs in middle and late Pleistocene alluvium in central New Mexico (Machette 1978), the slight timelag between deposition along main streams and their tributary systems may be a widespread phenomenon in semiarid environments of the Southwest.

The open-basin alluvium consists of moderate to well-sorted, medium to coarse sand and pebbly to bouldery gravels. The alluvium of Holocene and latest Pleistocene age is commonly light gray to very light brown, whereas the older alluvium is light reddish brown to reddish brown. The color distinction reflects postdepositional accumulation of clay and oxidation of weatherable minerals in the alluvium. As originally deposited, there appear to be no significant, systematic differences in texture, sorting, or color for the various units of open-basin alluvium.

TEPHRA OF RANCH CANYON

The tephra of Ranch Canyon (figs. 3 and 4, Qrct; terminology of Lipman and others 1978) consists of obsidian and pumice that were erupted from rhyolite domes (fig. 2, Qr) along the crest of the central Mineral Mountains. Sanidine extracted from the tephra was dated at 0.55 ± 0.01 m.y. by the potassium-argon method (Izett 1981, p. 10215). In the Beaver Basin, the tephra was deposited as a local blanket of airfall material and then reworked and deposited in stream channels graded to and directed toward the basin outlet at Minersville Reservoir (figs. 2 and 5). The tephra is best exposed along Cunningham Wash, where it fills a deep stream channel that is cut well below the base of the adjacent basalt of Cunningham Hill. The Ranch Canyon tephra is 10–12 m thick in road cuts along Cunningham Wash; exposures in quarries to the north are even thicker. Basalt boulders in the basal part of the channel fill demonstrate, independent of the K-Ar age determinations, that the tephra is younger than the basalt (1.1 m.y.).

Cunningham Wash and, by inference, other streams in this part of the basin must have been deeply incised by 550,000 years ago. Scattered outcrops of the tephra are found near the present stream level along Cunningham Wash, Wildcat Creek, and Indian Creek as far south as Adamsville (fig. 2). These relations strongly suggest that middle Pleistocene streams in the west part of the basin were incised well below the level of early Pleistocene streams as marked by the position of the basalt of Cunningham Hill. They also show that the middle Pleistocene streams flowed toward an outlet at Minersville Canyon, not toward the central part of the basin as they did during the early Pleistocene.

GRAVEL OF LAST CHANCE BENCH

The gravel of Last Chance Bench lies on a pediment cut across closed-basin sediment in the central and northeastern parts of the Beaver Basin. The gravel is named for the widespread surface that it forms, Last Chance Bench. The bench is preserved as a continuous surface from the west front of the Tushar Mountains, between Indian Creek and North Creek, westward 20 km to near Adamsville (figs. 2 and 6). Isolated erosional remnants of the gravel form "The Hogsback" surface between Wildcat Creek and Indian Creek, the high surfaces south and east of Cedar Knoll, and the surfaces mantled by basalt boulders on the north flank of the Black Mountains. As a result of extensive middle to late Pleistocene faulting, the gravel of Last Chance Bench is from 30 m to more than 100 m above stream level; commonly it occurs at levels of about 75 m above present stream level. Near the mouth of North Creek (fig. 2), Last Chance Bench lies 20–50 m above North Creek, a level that is about 25 m below the adjacent, but older, Table Grounds surface (the depositional top of the closed-basin sediment; fig. 5).

The gravel of Last Chance Bench consists of light brown to reddish brown, well-sorted pebbly sand to sandy gravel. Near the mountain front, the gravel has texture similar to the underlying fanglomerate facies of the closed-basin deposits. However, toward the center and southwest portions of the basin, the gravel of Last Chance Bench lies in angular unconformity on lacustrine-facies sediment (QTsl) of much finer texture. Although

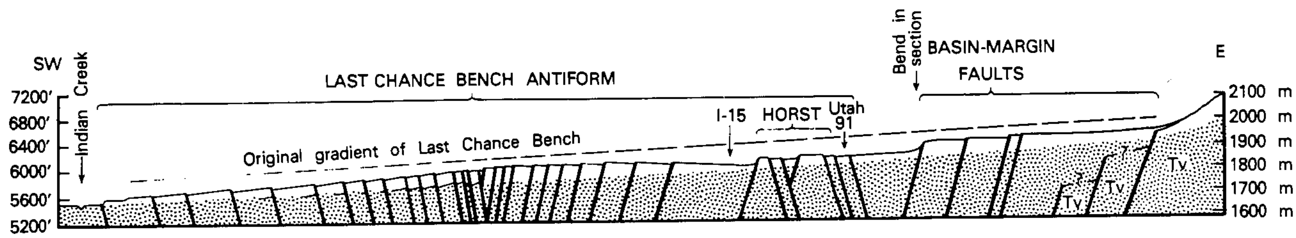


FIGURE 6.—*Generalized southwest-to-east section across the central part of the Beaver Basin showing position of Last Chance Bench antiform and basin-margin faults. Dashed line is parallel to and 30 m (100 ft) above the original gradient of Last Chance Bench. Huckleberry Ridge ash bed (2.0 m.y.), which is exposed on the west limb of the antiform, is shown by a thin line 20–50 m below the bench. The stipple pattern indicates the general level of exposure in the basin. Tv, Tertiary volcanic rocks.*

the gravel is generally only 2–5 m thick, it forms a protective mantle over the closed-basin sediment.

The gravel of Last Chance Bench must be about 500,000 years old, based on radiometric ages which bracket it. Reworked Ranch Canyon tephra is present in the basal part of the gravel about 5 km north of Manderfield, in the large west-facing roadcut of U.S. Highway 91 (fig. 2). Therefore, the maximum age of the gravel must be less than 550,000 years old, because some time is needed to complete deposition of the overlying gravel. The minimum-age limit comes from a preliminary uranium-trend soil age of 390,000 ± 70,000 years (Steer 1980; modified by J. N. Rosholt in 1981, written communication 1983), determined by the method described by Rosholt (1980). The uranium-trend age is from a soil in fault-scarp colluvium that was derived from the Last Chance Bench gravel (Machette 1982, field trip stop 2). Thus the 390,000 year age is considered to be an absolute minimum for the gravels of Last Chance Bench. However, on the basis of the two radiometric ages and depositional considerations, it appears that the gravels were deposited about 500,000 ± 25,000 years ago.

GRAVEL OF INDIAN CREEK

The next youngest open-basin sediment is the gravel of Indian Creek (Qic; figs. 3 and 5). This gravel forms a narrow terrace 5–12 m below the gravel of Last Chance Bench along the southern portion of The Hogsback. Further downstream, the gravel of Indian Creek caps a ridge 30–38 m above the stream level of Indian Creek. It is named for a 2- to 5-m-thick channel-filling gravel that marks an ancestral course of Indian Creek, northward of its present position. The ancestral channel is fault-controlled, although deposition of the alluvium was probably controlled by climatic fluctuations. I have no direct age data for the gravel of Indian Creek, but constraints from younger and older alluvium suggest an age of 350,000–400,000 years.

ALLUVIUM OF NORTH CREEK

The alluvium of North Creek (Qnc, figs. 3 and 5) forms a 5- to 10-m-high terrace along the north side of North Creek between the small community of North Creek on the east and U.S. Highway 91 on the west (fig. 2). This alluvium was mapped as the oldest of three major alluvial units, and was previously designated "old alluvium" (Machette 1983; Machette and Steven 1983; Machette and others 1983). The alluvium of North Creek is preserved below a narrow terrace 16–18 m above the Beaver River near Greenville and forms small islands that are buried by younger alluvium 20–25 m above Indian Creek near Manderfield (fig. 5). The alluvium of North Creek is much higher in the north part of the basin, where it lies about 60–65 m above Fortuna Canyon. Although the terraces are underlain by only 3–5 m of alluvium of North Creek, as much as 10 m of alluvium may be present in channels along major streams.

The bulk of the alluvium of North Creek was deposited about 250,000 years ago. Steer's (1980) uranium-trend age from soil in this alluvium is 290,000 ± 80,000 years (revised by J. N. Rosholt in 1981, written communication 1983; see also Machette 1982, field trip stop 3). An age of 250,000 years for the alluvium of North Creek is supported by the soil development in this unit and the soil's content of pedogenic calcium carbonate. This alluvium is about the same age as deposits of the last major pre–Bull Lake glaciation in the Rocky Mountains (terminology of Colman and Pierce 1981) and the Slocum alluvium of the Colorado Piedmont (Machette 1985).

ALLUVIUM OF GREENVILLE

The alluvium of Greenville forms a narrow alluvial terrace that lies 12–13 m above the Beaver River, west of Greenville. This alluvium was mapped as the middle of three major alluvial units, and was previously designated "middle alluvium" (Machette 1983; Machette and Steven 1983; Machette and others 1983). The alluvium of

Greenville (Qgv, figs. 3 and 5) forms terraces along major streams in the Beaver Basin and slightly dissected piedmont surfaces graded to these terraces. In the central part of the basin, Greenville terraces are 10–13 m above Indian Creek but rise to 40–45 m above Chokecherry Hollow just south of Gillies Hill (fig. 2). The alluvium is commonly 2–5 m thick where it forms terraces along the Beaver River and 4–10 m thick in alluvial fans.

Along South Creek in the southern part of the Beaver Basin, the alluvium of Greenville forms three stratigraphically separate terraces as a result of repeated faulting. A uranium-trend age of 160,000 ± 160,000 years (Steer 1980; revised by J. N. Rosholt in 1981, written communication 1983) was obtained from a soil in the middle terrace of alluvium of Greenville along South Creek. The parent materials of this soil appear to be of two ages, with younger alluvium over older alluvium of Greenville. Hence, the large error limits are a result of only having three samples from each parent material, instead of the usual six to eight samples. On the basis of soil development, I interpret the lower part of this soil as the main phase of the alluvium of Greenville that forms a single terrace elsewhere in the basin. Thus the upper part of the alluvium (the middle terrace) and all of the next, lower terrace are interpreted as young phases of the alluvium of Greenville that were deposited in response to episodic movement on a basin-margin normal fault (Machette unpublished map data 1983).

The bulk of the alluvium of Greenville was deposited about 140,000 years ago. This age is based on the development of soils in the alluvium and the uranium-trended age. The alluvium of Greenville is about the same age as deposits of the Bull Lake glaciation in the Rocky Mountains (terminology of Colman and Pierce 1981) and the Louviers Alluvium of the Colorado Piedmont (Machette 1985).

ALLUVIUM OF BEAVER

The alluvium of Beaver (Qbv, figs. 3 and 5) forms a major terrace and floodplain on which the town of Beaver is built. This alluvium is designated as "young alluvium" on recent geologic maps of the basin. A large body of this alluvium lies between North Creek and the Beaver River, from west of Beaver to the base of the Table Grounds. The alluvium forms a broad, slightly elevated and coalesced surface 3–6 m above the level of the Beaver River, west of Beaver, and terraces 3–5 m above Indian Creek near Manderfield (fig. 2).

An anomalously old uranium-trend age of 27,000 ± 8,000 years was obtained from soil in the alluvium of Beaver (Steer 1980; recalibrated by J. N. Rosholt in 1981, written communication 1983). On the basis of soil development, I consider the alluvium of Beaver to be correlative with deposits of the most recent major glaciation—the Pinedale—which probably ended 15,000 to 12,000 years ago (Colman and Pierce 1981). The alluvium of Beaver also is correlative with the Broadway Alluvium of the Colorado Piedmont (Machette 1985).

HOLOCENE ALLUVIUM

The youngest alluvial unit in the Beaver Basin consists of Holocene floodplain and fan alluvium (Qfp, fig. 5). The Holocene alluvium forms broad, undulatory surfaces along the Beaver River and North Creek west of Beaver. Toward the Tushar Mountains, the alluvium forms narrow channels cut 1–3 m into the alluvium of Beaver. Along the lower reaches of Wildcat and Indian Creeks, the Holocene alluvium is fine grained and includes beds of massive silt and fine sand. Here the Holocene alluvium contains abundant organic matter and calcium carbonate that were deposited in a marshlike environment.

SOILS

Soils are a fundamental tool for deciphering the Quaternary geologic history in the Beaver Basin. Soils are used in mapping and correlating the open-basin sediments and for making estimates of their age. Soils are especially important in this study because Pleistocene faulting has deformed and displaced the Pleistocene alluvium. As a result, vastly different ages of alluvium often lie at similar levels. Therefore, alluvial units cannot be divided solely on the basis of their height above stream level over most of the Beaver Basin.

The soil-chronosequence concept of Harden and Marchand (1977) was used in the Beaver Basin to study the influence of time on soil development. By definition, a soil chronosequence is formed in parent materials of similar lithologies and textures, in similar landscape positions, and in similar biotic, vegetative, and climatic environments. If these factors are comparable for all the soils of the chronosequence, then the main differences in soil development are a product of time, or duration of soil formation.

For the purposes of this study, I described, sampled, and analyzed only relict soils, as defined by Ruhe (1965) and as used by Birkeland (1984); that is, soils that have formed continuously since the deposition of their respective parent materials (host deposits). Accordingly, the age of a relict soil may closely approximate the age of the parent material. Conversely, buried soils reflect the amount of time that they were at the surface.

The Beaver soil chronosequence spans the past 750,000 years of the Pleistocene. These soils are formed in the youngest part of the closed-basin sediment, which underlies the Table Grounds surface, and subsequent alluvial units deposited under open-basin conditions (fig. 5). The parent materials are mainly pebbly to sandy gravels derived from Miocene mafic to silicic volcanic rocks in the Tushar Mountains and in the Black Mountains. Throughout the basin a 5- to 20-cm-thick layer of desert loess and fine-grained eolian sand of mixed lithology has accumulated locally on stable physiographic surfaces.

CLIMATE

The continental climate of the Beaver Basin ranges from semiarid (20–25 cm of moisture) in the lower elevations to dry-subhumid (25–30 cm of moisture) along the margins of the basin at elevations below 2,100 m (6,900 ft) (Stott and Olsen 1976). Precipitation during the winter and spring months accounts for about 70 percent of the yearly total. The mean annual air temperature is 7°–9° C at elevations of 1,585–2,100 m (5,200–6,900 ft) in the basin. The average monthly minimum (−10° C) and average monthly maximum (30° C) temperatures occur in January and July, respectively.

During the Holocene, the climate in the Southwest has been relatively dry, as indicated by the relatively shallow levels at which $CaCO_3$ and other soluble salts have precipitated in the soils. In the Beaver Basin, Holocene $CaCO_3$ has accumulated at depths of 30–100 cm. Yet, because the basin is relatively high (1,585–2,100 m altitude), it is near the upper precipitation limit for carbonate accumulation (the pedocal regime). Thus, some soils at high altitudes in the Beaver Basin may have periodically lost $CaCO_3$ during wetter climatic intervals such as that of the Pinedale glaciation.

SOIL DATA

Although this report focuses on the late Cenozoic history of the Beaver Basin, I have included some selected physical and chemical data for the Beaver soils in table 1. Although this listing is not comprehensive, it shows some time-related soil properties that have proved useful in dividing the Quaternary alluvium in the Beaver Basin. Abbreviations used in this table are based on common soil terms; readers unfamiliar with this terminology should consult Soil Taxonomy (Soil Survey Staff 1975) or references on soils and geology such as Birkeland (1984). The terminology for Cca and K horizons follows Gile, Peterson, and Grossman (1965). Carbonate morphology stages I through IV are described according to criteria of Gile, Peterson, and Grossman (1965) and of Bachman and Machette (1977).

The summary of soil data is based on descriptions of 25 soil profiles and on selected laboratory data such as texture, $CaCO_3$ content, bulk density, and saturation pH. A complete list of field descriptions and laboratory data and discussion is presented in Machette (1982). The laboratory methods are those reported in Machette and others (1976).

SUMMARY OF SOIL DEVELOPMENT

The properties and horizons of soils in the Beaver Basin show systematic trends with time that provide a basis for evaluating the age of other soils in similar climatic regimes of the eastern Basin and Range Province and may provide a basis for extending the stratigraphic framework of the open-basin sediment westward into the eastern Basin and Range Province. Although I collected data on most soil properties, such as pH, organic matter content, structure, and texture (Machette 1982), the following discussion focuses on two main characteristics: the development of B horizons and development of Cca and K horizons. These two indicators of soil development appear to have the most direct and quantitative relation to soil age.

B HORIZONS

Clay enriched (argillic) horizons are present in all but the Holocene soils of the Beaver Basin. Argillic B horizons are barely perceptible to incipiently developed in soils formed in the alluvium of Beaver (latest Pleistocene), but show progressive development in the soils formed in the alluviums of Greenville (140,000 years old) and North Creek (250,000 years old). The strength and coarseness of ped structures in these horizons also increase with time in response to increasing clay content. Progressive development of argillic B horizons in even older soils (those below the Last Chance Bench (500,000 years old) and Table Grounds (750,000 years old) surfaces) is masked by engulfment from upward-migrating horizons of calcium carbonate and minimized by erosion of the B horizon from long exposure at the surface.

CALCIC HORIZONS

Although the soils of the Beaver Basin are marked by accumulations of calcium carbonate, their parent material is noncalcareous to very weakly calcareous (less than 2 percent $CaCO_3$). Because there is no evidence of deposition of $CaCO_3$ in the alluvial units by shallow groundwater, I conclude that most or all of the $CaCO_3$ in these soils is derived from aerosolic sources such as calcareous eolian sand and dust and from Ca^{++}-enriched rainfall (Gile and others 1966; Bachman and Machette 1977; Gile and Grossman 1979; Machette 1985).

The soil below the Table Grounds surface has a stage IV K horizon, marked by thin laminae and as much as 65 percent $CaCO_3$ in the <2 mm fraction of the soil (table 1). The total secondary $CaCO_3$ content of this soil is 51–66 g/cm^2. These values should be considered as minimums because my 2- to 3-m-deep sampling pits did not extend to the base of the calcic horizon.

Calcic soils in the 500,000-year-old gravel of Last Chance Bench have an average of 70 ± 5 g/cm^2 of $CaCO_3$.

Table 1. Comparison of Some Properties of Soils Formed in Pleistocene Alluvium of the Beaver Basin, Southwestern Utah

[Abbreviations in headings are as follows: t, thickness; *Clay, difference in clay content between maximum value in horizon and that of the A horizon (A) or the C horizon (C); *$CaCO_3$, maximum percent calcium carbonate in less-than-2-mm fraction. Other abbreviations are as follows: thickness values in parentheses are total thickness of clay accumulation in soil; *$CaCO_3$ values in parentheses are maximum percent calcium carbonate in the whole-soil fraction; Munsell color notation is m (moist) and d (dry); modifiers for maximum stage of carbonate are − (weak) and + (strong).]

	B horizon			Cca/K horizon				
Soil number and location[1]	t, in cm	Maximum color (Munsell)	*Clay	t, in cm	Maximum Stage	*$CaCO_3$	Total $CaCO_3$, in g/cm^2	Remarks
SOIL IN ALLUVIUM OF BEAVER (LATEST PLEISTOCENE, 12,000–15,000 YRS)								
No. 1 Beaver Ready Mix	30	5YR5/3 to 5/4d	3(A)	100	I	0.4 (.1)	n.d.	High water table
No. 2 Country Inn	35	7.5YR4/4d to 5/4d	3(A)	20–120	II−	.7 (.1)	n.d.	High water table
No. 3 Manderfield Church	25	7.5YR4/4m	4(A)	110	I+	1.9 (.2)	0.3	
TYPICAL VALUES	30	7.5YR5/4d	3(A)	100	I+	2.0 (.1)	<0.3	Age: 12,000–15,000 yr
SOIL IN ALLUVIUM OF GREENVILLE (LATE PLEISTOCENE, 140,000 YRS)								
No. 4 Field trip stop 5	17	5YR5/3d to 5/4d	8(A) 20(C)	56	III	32 (30)	11	
No. 5 Greenville dump	31	7.5YR5/4m	18(A) 29(C)	53	III−	27 (26)	8	Thin profile, $CaCO_3$ lost
No. 6 LDS Farm	45	7.5YR5/5m	11(A) 16(C)	52	III−	16 (10)	6	Leached, high water table
TYPICAL VALUES	30	7.5YR5/4d	12(A) 22(C)	54	III−	25 (22)	10–12	Age: 140,000 yr
SOIL IN ALLUVIUM OF NORTH CREEK (MIDDLE PLEISTOCENE, 250,000 YRS)								
No. 7 Field trip stop 4	60(85)	5YR5/6d	7(A) 25(C)	118	III	47 (24)	25	Loess over gravel
No. 8 Greenville cemetery	35(68)	5YR5/6d	25(A) 32(C)	>85	III	15 (11)	>9	Thin on QTs, $CaCO_3$ lost
No. 9 Field trip stop 3	47(88)	5YR6/6d	18(A) 25(C)	115	III	40 (32)	38	Thick, U-trend age: 290,000 yr
TYPICAL VALUES	51(80)	5YR5/6d	17(A) 27(C)	106	III	44 (28)	32 ± 4	Age: 250,000 yr
SOIL IN GRAVEL OF LAST CHANCE BENCH (MIDDLE PLEISTOCENE, 500,000 YRS)								
No. 10 U.S. Hwy 91 pit	35(107)	7.5YR4/3d	8(A) 28(C)	127	III+	59 (59)	78	Max clay in K horizon
No. 11 Field trip stop 2	67(132)	5YR5/6d	23(A) 32(C)	>133	III+	53 (38)	49	Base covered, min. $CaCO_3$
No. 12 Upper BLM pit	18(100)	5YR4/4m	10(A) 24(C)	132	III+	68 (67)	70	U-trend age: >390,000 yr
TYPICAL VALUES	40(100)	5YR5/5d	14(A) 28(C)	130	III+	60 (55)	70 ± 5	Age: 500,000 yr
SOIL BELOW TABLE GROUNDS SURFACE (LATEST EARLY PLEISTOCENE, 750,000 YRS)								
No. 13 Field trip stop 1	none	n.d.	n.d.	>110	IV	50 (46)	>51	Eroded, cov'd base, min. $CaCO_3$
No. 14 BLM pit	27	7.5YR5/4m	n.d.	>150	IV	65 (62)	66	High altitude, $CaCO_3$ lost
TYPICAL VALUES	stripped consumed	7.5YR5/4m	n.d.	150?	IV	65 (62)	>66	Age: 750,000 yr; $CaCO_3$ lost

[1]Location of field trip stops shown in Machette 1982.

Assuming that this value accurately reflects the soil's total secondary carbonate content, then the average rate of $CaCO_3$ accumulation during the past 0.5 m.y. is 0.14 ± 0.01 g for a column of 1 cm^2 surface area. The soils in gravel of Last Chance Bench commonly have well-developed, 130-cm-thick K horizons having a maximum carbonate content of about 60 percent (table 1). The calcic horizons have advanced stage III morphology characterized by massive accumulation of carbonate and platy structure; however, laminae (stage IV morphology) are not present.

By comparison, soils in 250,000-year-old alluvium of North Creek have thinner and less calcareous calcic horizons that contain slightly less developed stage III morphology (table 1). These latter soils typically contain about 32 g of secondary $CaCO_3$ per cm^2. If one assumes that this amount of $CaCO_3$ accumulated at a rate of 0.14 g/cm^2, then the secondary carbonate in the calcic horizons would have formed over an interval of 230,000 years. This interval compares quite favorably with Steer's (1980) uranium-trend age of 290,000 ± 80,000 years.

The soils in alluvium of Greenville are the youngest that have significant accumulations of carbonate. Their calcic horizons are typically 50 cm thick and are characterized by weakly developed, discontinuous stage III morphology having a maximum of about 25 percent $CaCO_3$. Although the distribution of carbonate suggests that some carbonate has been periodically leached from the soils, they still contain as much as 10–12 g of $CaCO_3$/cm^2 (table 1). These contents require 70,000 to 85,000 years to accumulate at the average rate determined for the past 500,000 years. However, the 70,000–85,000-year-interval should be considered as a minimum value for two reasons. First, the partial depletion of carbonate will cause the calculated secondary carbonate contents to be minimum values. Second, during the past 125,000 years (essentially the last major glacial-interglacial episode) the average carbonate accumulation rate may have been slower than that over the past 500,000 years (Machette 1985). Nevertheless, these data clearly show that the calcic soils in alluvium of Greenville require a substantial amount of time to form; perhaps 10 times as long as those in the next younger alluvial unit, the alluvium of Beaver.

In the southeast part of the basin, the soils in the alluvium of Beaver are noncalcareous. Here a high level of groundwater has prevented accumulation of significant soil carbonate in the alluvium of Beaver and the Holocene alluvium. However, to the north and west where the alluvium of Beaver is well above the local level of groundwater, its soil contains about 2 percent $CaCO_3$ as thin continuous coatings of carbonate (stage I) on clasts extending from about 30 cm to more than 100 cm deep in the soil.

Soils in the Beaver Basin that are 500,000 years old accumulated $CaCO_3$ at an average rate of 0.14 ± 0.01 g/cm^2 per 1,000 years. This rate is relatively slow in comparison to those determined from other areas of the Southwest. For example, 500,000-year-old soils from three areas of New Mexico show average accumulation rates of 0.26–0.52 g/cm^2 per 1,000 years, rates which are 2–4 times faster than at Beaver. The slower rates in the Beaver Basin are explained mainly by lesser amounts of Ca^{++} supplied to the surface by either rainfall or eolian contributions (Machette 1985).

PLIOCENE AND PLEISTOCENE DEFORMATION

There are two deformational systems active in the Beaver Basin. The first is related to the progressive growth of the Maple Flats horst and the Last Chance Bench antiform; the second may be related to episodic extensional faulting along the east side of the basin, which appears to be the active transition zone between the Basin and Range and Colorado Plateau Provinces. The Maple Flats horst in the north part of the basin and the axis of the Last Chance Bench antiform in the central to south part of the basin lie on the same trend, which suggests a causal relation between the two features. Indeed, the antiform may be the surficial expression of the horst structure at depth.

The Maple Flats horst was a positive structural and topographic feature during closed-basin deposition in Miocene and Pliocene time. The Maple Flats horst extends southward as a topographically high block nearly to Wildcat Creek, where the conglomerate of Maple Flats (Tsmf) is in fault contact with upper Pliocene to lower Pleistocene lacustrine sediment (QTsl). This horst was a peninsula that extended south into Lake Beaver, as shown by the areal deposition of the Huckleberry Ridge ash bed (2.0 m.y.) in lacustrine sediment adjacent to the central part of the horst, but not on it. Pleistocene uplift of the horst is shown by 10°–15° rotation of the Huckleberry Ridge ash bed, outward from the horst.

The basalt of Cunningham Hill, which flowed across the southern end of the Maple Flats horst about 1.1 m.y. ago, is now displaced by a series of north-trending, down-to-the-east normal faults that are antithetic to the west-bounding fault of the horst. Movement on these faults has tilted the basalt as much as 5° to the west, such that it appears to have flowed northward, rather than southward. Together, these faults displace the basalt at least 100 m and show that during the Pleistocene either the Maple Flats horst continued to be uplifted or its adjacent areas continued to subside.

Farther to the south along The Hogsback, upper closed-basin sediments are tilted as much as 20° away from the southward projection of the horst (Machette 1983) and are unconformably overlain by the gravel of

Last Chance Bench. Post-500,000-year movement on north-trending faults displaces The Hogsback surface as much as 5 m locally. These faults represent the northern extension of the Last Chance Bench antiform.

The antiform has the shape of a broad keystone that is best exhibited in the gravels of Last Chance Bench (fig. 6). The limbs of the antiform, which dip gently away from the axis, are cut by as many as 100 closely spaced normal faults that strike north to 20° east of north. The axial trace of the Last Chance Bench antiform (fig. 2; Machette and others 1983) is offset about 2.4 km to the west by northeast-striking faults spaced over a distance of 10 km between Wildcat Creek on the north and the Beaver River on the south. Although this second set of faults has down-to-the-northwest displacement, they are contemporaneous with the main set of north-striking normal faults. North of Indian Creek, the north-trending faults displace The Hogsback surface and, to a lesser extent, the alluviums of North Creek and Greenville east of The Hogsback. The southwest-trending valley of Indian Creek probably is fault controlled; such a fault would explain the 30–100 m difference in the altitudes of the Last Chance Bench and The Hogsback surfaces.

Upper Pliocene closed-basin sediments below Last Chance Bench dip as much as 20° near the axis of the antiform and horst, but less than 5° several kilometers to the east and west on the limbs of the antiform (fig. 6). The abrupt change in attitude across the antiform shows that most of the tilting occurs in a narrow zone along the axis of the antiform. However, there has been almost no structural relief produced across most of the Last Chance Bench antiform during Pleistocene time as demonstrated by the roughly similar altitude of the Huckleberry Ridge ash bed where it crops out on the west limb of the antiform (fig. 6) and elsewhere in the center of the basin.

Both the northeast- and north-trending faults form sharp topographic and vegetation lineaments on Last Chance Bench. The combination of both north- and northeast-striking faults has tilted the bench gently to the south, such that the surface of the bench projects below stream level along the Beaver River from Greenville to Adamsville. Ephemeral streams on the bench flow either southwest or south along the base of the fault scarps and tend to funnel runoff into the south central part of the basin.

The Last Chance Bench antiform extends as far south as the north bank of the Beaver River where the alluviums of Greenville and North Creek form terraces and broad piedmont slopes graded to the terraces. A series of closely spaced, north-striking normal faults forms 0.5- to 3-m-high scarps on these terraces. The pattern and orientation of these faults are in every way identical to those to the north on Last Chance Bench and indicate the antiform continued to form in the late Pleistocene.

East of the antiform, individual basin-margin faults displace the gravel of Last Chance Bench. With the exception of a major horst just east of I-15 (fig. 6), these faults are predominantly down to the west. The basin-margin faults produce about 100 m of net down-to-the-west displacement on Last Chance Bench. Many of these faults can be traced both north and south into younger alluvial units where they have proportionately less displacement.

AGE OF FAULTING

Many of the scarps formed by the basin-margin faults and those associated with the Last Chance Bench antiform range from 5 to 25 m in height. These faults commonly show a progressive increase in scarp height in relation to the age of alluvium that they cut. For example, scarp heights along the Beaver fault illustrate well the repeated Pleistocene movement along many of the faults in the Beaver Basin. The Beaver fault (Steer 1980) extends from the Beaver River, on the south, to Indian Creek, on the north. It forms an arcuate, west-curving fault scarp that is 1–3 m high in the latest Pleistocene alluvium of Beaver between the town of Beaver and North Creek. Farther north, the fault forms an 11-m-high scarp in the 250,000-year-old alluvium of North Creek and a 25-m-high scarp in the 500,000-year-old gravel of Last Chance Bench (Machette and others 1983). These scarp heights clearly show progressive displacement along the Beaver fault.

The 1- to 3-m-high fault scarps in the alluvium of Beaver were produced by a single surface rupture, as shown by Steer's (1980) trench investigations. If one assumes that individual ruptures along the fault produce about 2 m of surface offset, then the large scarps to the north record about five events since 250,000 years ago and 12 events since 500,000 years ago. The number of events thus calculated are minimal values, because the height of a scarp is commonly more than the net throw on the fault. These simplistic calculations yield average recurrence intervals of about 50,000 years for 2-m displacements on the Beaver fault.

Stratigraphic evidence and morphometric data on fault scarps show that many of the faults in the Beaver Basin have had latest Pleistocene movement (Bucknam and Anderson 1979; Steer 1980). Steer (1980) and R. E. Anderson (written communication 1982) independently measured scarp profiles of the Beaver fault and a similar fault (nos. 48 and 49, respectively, of Steer 1980) about 1 km east of the Beaver fault (fig. 7), both of which displace the alluvium of Beaver. These two fault scarps have maximum scarp-slope angle (θ) and scarp-height (H) values that are similar to, but slightly less degraded than the highest wave-cut shoreline of Lake Bonneville (Bucknam and Anderson 1979), which Scott and others (1983) demonstrate to be 14,000–15,000 years old. However, the fault scarps are more degraded than those along the Drum Mountains fault. Recent studies by Crone (1983) suggest that the Drum Mountains fault scarps are either early Holocene or latest Pleistocene in age. Thus, by comparison, the two fault scarps in the alluvium of Beaver (uppermost Pleistocene) must have been formed during latest Pleistocene or earliest Holocene time.

URANIUM MINERALIZATION IN THE BEAVER BASIN

Steven and others (1981) noted that the Beaver Basin had long been a structural sump for water draining uranium source areas in the Tushar and Mineral Mountains. Geochemical surveys by Miller and others (1980), a helium survey by Reimer (1979), and radon surveys by McHugh and Miller (1982) strongly suggest that uranium is concentrated in the closed-basin rocks. Shallow groundwater along the Beaver River is saturated with uranium according to chemical studies by Miller and others (1980) and Miller and McHugh (1981). Recently, industry has made surveys of soil-radon concentrations (see data of S. M. Hansen in Steven and others 1981) and drilled numerous 150- to 450-m-deep test holes in the pre-Pleistocene sedimentary rock between Wildcat Creek, Manderfield, and the Beaver River. Although the results of these drilling activities are not known to the U.S. Geological Survey, the level of interest displayed by industry suggests that uranium is present in the closed-basin sedimentary rocks of the Beaver Basin.

Several conclusions from this study bear on the potential for concentrating uranium in the Beaver Basin. The basin contains a 1,500- to 2,000?-m-thick sequence of closed-basin sedimentary rocks that date back to Miocene time. Buried parts of these rocks, particularly those deposited in a lacustrine environment, probably contain significant carbonaceous material that was deposited under reducing conditions. Changes in texture, porosity, and permeability of the different closed-basin facies over short vertical and lateral distances cause both chemical and lithological discontinuities that could be favorable for uranium precipitation. Development of folds and faults associated with the antiform and horst along the central axis of the basin has undoubtedly influenced the flow of

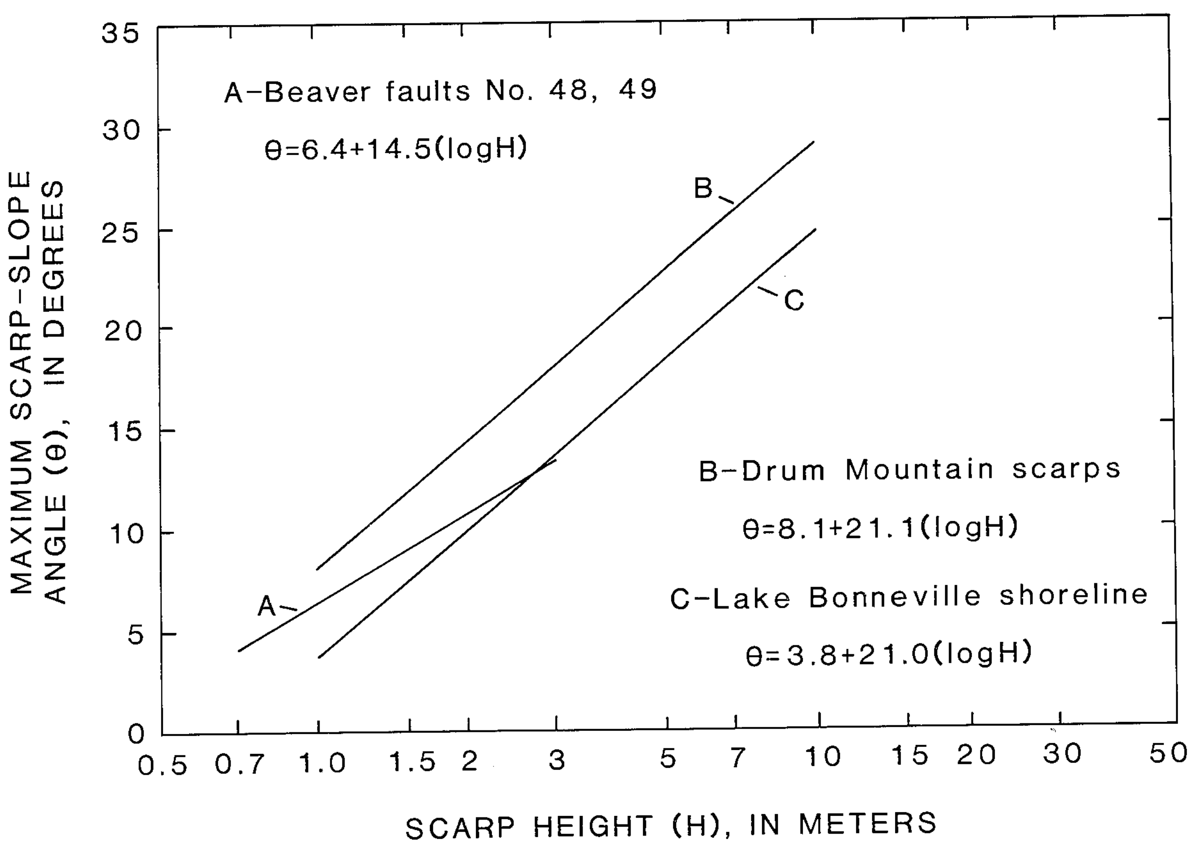


FIGURE 7.—*Morphometric data for late Pleistocene to Holocene fault scarps near Beaver. (A) Steer's (1980) Beaver faults, nos. 48 and 49. (B) Early(?) Holocene fault scarps near the Drum Mountains (Bucknam and Anderson 1979; Crone 1983). (C) Scarps of the 14,000–15,000-yr-old shoreline of Lake Bonneville (R. C. Bucknam written communication 1982; Scott and others 1983).*

groundwater, and the recurrent growth of these features may have caused groundwater flow patterns to change many times during late Cenozoic time. Finally, until open-basin conditions were established about 750,000 years ago, the basin had a high water table that perpetuated reducing environments in the subsurface. Together, these factors create a favorable environment for secondary uranium mineralization in the upper Cenozoic sedimentary rocks of the Beaver Basin.

CONCLUSIONS

Pleistocene erosion in the Beaver Basin has exposed upper Cenozoic sediments rarely seen in the Basin and Range portion of central Utah. These sediments record a history of nearly continuous middle(?) Miocene to early Pleistocene closed-basin deposition and middle Pleistocene to Holocene open-basin deposition. The upper several hundred meters of these sediments contain five distinct beds of volcanic ash that range from about 2.4–1.6 m.y. in age and a 1.1-m.y.-old basaltic lava. Most of the ash beds are preserved in the upper Pliocene lacustrine sediments of Lake Beaver.

About 750,000 years ago, Lake Beaver was drained by the opening of an outlet at the southwest corner of the basin. By 500,000 years ago, the gravel of Last Chance Bench was deposited on a broad pediment surface across most of the basin. Subsequent deposition has left the following, mainly erosional sequence of terrace and piedmont-slope alluvium: the Indian Creek (350,000–400,000 years old), North Creek (about 250,000 years old), Greenville (140,000 years old), and Beaver (12,000–15,000 years old). These units were deposited in response to changes in climate and to progressive lowering of local baselevel along the Beaver River and its tributaries. Over the past 500,000 years, relict soils in the Beaver Basin have accumulated $CaCO_3$ at an average rate of 0.14 ± 0.01 g per square centimeter of soil column every 1,000 years.

Upper Cenozoic sediments are uplifted in the Maple Flats horst near the north end of the basin and deformed into the broad south-plunging antiform of Last Chance Bench in the south central part of the basin, and along a 4-km-wide zone at the base of the Tushar Mountains. Most of these faults have a history of episodic, recurrent movement as recent as late Pleistocene. The stratigraphic and structural relations recognized in the Beaver Basin suggest that many of the adjacent basins of the western Colorado Plateau and eastern Basin and Range Provinces also contain potentially datable upper Cenozoic sediments. The soil data and age determinations from open-basin alluvium in the Beaver area can help map and correlate the Quaternary deposits in many of the adjacent basins.

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