

PRELIMINARY GEOLOGIC MAP OF THE
EASTERN PART OF THE GALLATIN VALLEY, MONTANA

by

Jeffrey D. Lonn¹ and Alan R. English²

Montana Bureau of Mines and Geology
Open File Report 457

2002

¹Montana Bureau of Mines and Geology, Montana Tech, Butte, MT 59701

²Gallatin Local Water Quality District, Bozeman, MT 59715

This report has had preliminary reviews for conformity with Montana Bureau of Mines and Geology's technical and editorial standards.

Partial support has been provided by the STATEMAP component of the National Cooperative Geologic Mapping Program of the U.S. Geological Survey under Contract Number 01-HQ-AG-0096.

Description of Lithologic Units

- Qal** **ALLUVIAL DEPOSITS OF ACTIVE CHANNELS AND PRESENT FLOOD PLAINS (HOLOCENE)**
Well-rounded, well-sorted, bouldery gravel and sand with some thin beds of clayey silt. Clast lithologies represent rock types of the entire watershed; along the West Gallatin River clasts are 50% Precambrian metamorphic rock, 45% igneous rocks (mostly mafic volcanics but including dacite porphyry and granite), and 5% sandstone and quartzite. Clasts along tributary streams represent the local bedrock. Often mantled with silty material deposited during floods caused mostly by ice jams (Mifflin, 1963). Older, underlying(?) deposits of Qaty, Qab, and Qat, are lithologically indistinguishable from Qal, and total thickness of these deposits ranges from 70 to 80 feet (22 to 25 meters) south of Bozeman Hot Springs to over 800 feet (246 meters) near Belgrade (Hackett and others, 1960). High permeability and porosity make this package an important aquifer locally. However, shallow depth of aquifers hosted by thinner deposits may make them subject to contamination. Potential for flooding and a high ground water table place severe limitations on construction and septic systems (Custer and others, 2001).
- Qaf** **ALLUVIAL FAN DEPOSITS (HOLOCENE AND LATE PLEISTOCENE?)**
Poorly to well-sorted, rounded to sub-angular gravel, sand, silt, and clay. Surfaces have a distinct fan shape. Deposited by both stream flow and debris flow processes in alluvial fan environments; aquifer properties reflect deposits of these different processes (see below). Clasts are locally derived and, in general, grain size decreases and degree of sorting increases with distance from the mountain fronts. At least some of these fans are still active, mostly following forest fires. Less than 100 feet (31 meters) thick.
- Qafs** **ALLUVIAL FAN DEPOSITS, STREAM FLOW FACIES (HOLOCENE AND LATE PLEISTOCENE?)**
Well-rounded, moderately to well-sorted, bouldery gravel and sand with a minor amount of silt and clay. Differs from Qal, Qat, and Qab in being not as well-sorted, in containing only locally derived clasts, and in having distinct fan-shaped surfaces. Deposited during floods in braided streams emerging from the mountains. Some, such as the Cottonwood Fan along the Bridger Range, may still be active. Can host good aquifers and gravel pits, but water tables can be high and subject to contamination. High water tables can also place limitations on construction and septic systems.

- Qafd ALLUVIAL FAN DEPOSITS, DEBRIS FLOW FACIES (HOLOCENE AND LATE PLEISTOCENE?)
Sub-rounded to sub-angular, poorly to moderately sorted, bouldery gravel sand, silt, and clay. Clasts are locally derived. Deposited mainly by rapid debris flows. Some Qafd fans are probably still active. Generally hosts poor aquifers. The large boulders can hamper the placement of effective septic systems (Custer and others, 2001).
- Qafm ALLUVIAL FAN DEPOSITS, MUDDY FACIES (HOLOCENE AND LATE PLEISTOCENE?)
Poorly to moderately sorted deposits of silt and clay deposited in alluvial fans by muddy debris flows and sheet floods. Most are still active. Source rocks are silty Tertiary Sixmile Creek Formation(Tscs) or Cretaceous shales and mudstones.
- Qls LANDSLIDE AND EARTHFLOW DEPOSITS (HOLOCENE AND PLEISTOCENE)
Unsorted and unstratified mixtures of mud and boulders transported by mass movement down slopes. Characterized by irregular hummocky topography. Most commonly develop on slopes underlain by Cretaceous mudstone or Tertiary Sixmile Creek Formation. Landslides are poor places on which to build, especially since even inactive landslides have a tendency to become active in years of above-average precipitation, or to be reactivated by construction.
- Qlsa ACTIVE LANDSLIDE AND EARTHFLOW DEPOSITS (HOLOCENE)
Landslides and earthflows that are currently active as indicated by cracks, fresh scarps, and rotated vegetation.
- Qlso OLDER, INACTIVE LANDSLIDE AND EARTHFLOW DEPOSITS (EARLY PLEISTOCENE)
Large, clearly inactive landslides on the northern slopes of the Story Hills, developed in Sixmile Creek Formation and probably formed in the early Pleistocene (Griffith, 1982).
- Qaty ALLUVIUM OF YOUNGER TERRACES (HOLOCENE? AND LATE PLEISTOCENE)
Well-rounded, well-sorted bouldery gravel and sand with some thin beds of clayey silt. Clast lithologies are identical to those of Qal. Contact between Qal and Qaty is often indistinct, but surfaces of Qaty usually stand about 5 feet (1.5 meters) above the present floodplain, rising to 15 feet (4.6 meters) where the West Gallatin River emerges from its canyon. Probably the same age as Qab, deposited during the waning stages of Pinedale glaciation. High permeability and porosity

make this unit a potential aquifer, but like Qal, it may have high water tables hindering construction and the effectiveness of septic systems.

- Qab** **ALLUVIAL DEPOSITS OF THE BELGRADE BRAID PLAIN (HOLOCENE? AND LATE PLEISTOCENE)**
Well-rounded, well-sorted bouldery gravel and sand with some thin beds of clayey silt. Underlies the plain that extends from Bozeman Hot Springs to north of Belgrade. Clast lithologies are representative of bedrock in the West Gallatin River drainage: 40% Precambrian metamorphic rocks, 40% mafic volcanic rocks, 10% dacite(?) porphyry, 7% sandstone and quartzite, 2% limestone, and 1% chert. Deposited by a larger, braided Gallatin River during Pinedale glaciation. Qab in combination with lithologically similar units (Qal, Qat, Qaty) may be up to 800 feet (246 meters) thick in the Belgrade area (Hackett and others, 1960). Qal along the West Gallatin River appear to be slightly incised into Qab, but some other modern streams such as Hyalite Creek flow across the top of Qab. The contacts and relationships between Qab and Qal are indistinct and uncertain. Qab is an important aquifer, and does not severely limit construction or septic systems (Custer and others, 2001). The gravel pits near Belgrade are developed in this unit.
- Qat** **ALLUVIAL TERRACE DEPOSITS (PLEISTOCENE)**
Well-rounded, well-sorted, bouldery gravel and sand with some thin beds of clayey silt. Underlies a distinct terrace 10-25 feet (3-8 meters) above modern stream deposits. Clast lithologies are similar to adjacent Qal, Qaty, and Qab. Mifflin (1963) postulated that these terraces formed during Bull Lake glaciation. Present along the West Gallatin River, Cottonwood Creek, Big Bear Creek, and South Cottonwood Creek, but not along Hyalite Creek or Bozeman (Sourdough) Creek. Hosts sand and gravel deposits and good aquifers, and has decent septic system suitability.
- Qafo** **OLDER ALLUVIAL FAN DEPOSITS (PLEISTOCENE)**
Poorly to well-sorted, rounded to sub-angular gravel, sand, and silt with minor amounts of clay. Surfaces have distinct fan shape. Deposited by both stream flow and debris flow processes in alluvial fan environments; aquifer properties of these deposits reflect these different processes. Clasts are locally derived and, in general, grain size decreases and degree of sorting increases with distance from the mountain fronts. These fans are perched above modern deposits at several different levels that probably represent several different ages. They are no longer active. Most Qafo is less than 100 feet (31 meters) thick. Its thinness and elevated, drained nature probably make it unimportant as an aquifer, but it generally provides good foundation stability and septic system suitability.

- Qafso **OLDER ALLUVIAL FAN DEPOSITS, STREAM FLOW FACIES (PLEISTOCENE)**
Well-rounded, moderately to well-sorted, bouldery gravel and sand with a minor amount of silt and clay. Clasts are locally derived and surfaces have a distinct fan shape. Deposited in braided streams emerging from the mountains. Perched above modern deposits and no longer active. Can host good aquifers and some gravel pits.
- Qafdo **OLDER ALLUVIAL FAN DEPOSITS, DEBRIS FLOW FACIES (PLEISTOCENE)**
Sub-rounded to sub-angular, poorly to moderately sorted, bouldery gravel sand, silt, and clay. Clasts are locally derived. Deposited mainly by catastrophic debris flows. These fans are perched above modern deposits and are no longer active. Generally host poor aquifers. Boulders and poor percolation rates may hamper the effectiveness of septic systems.
- Qabo **OLDER ALLUVIUM OF BRAID PLAINS (EARLY PLEISTOCENE?)**
Well-rounded, moderately to well-sorted, bouldery gravel with interbedded silt. Underlies the northern part of the “Bozeman Fan” (Hackett and others, 1960). Deposited on and possibly incised into a pediment surface developed on Sixmile Creek Formation, but too thick to call pediment gravel. Probably deposited as glacial outwash during an early Pleistocene glacial period. Poorly exposed, but well logs suggest it is 15-30 feet (4-9 meters) thick. Groundwater in this unit is perched above the pediment surface and is found at shallow depths, limiting effectiveness and advisability of septic systems (Custer and others, 2001) and may hinder construction.
- QTdf **DEBRIS FLOW DEPOSIT OF THE DEER CREEK AREA (EARLY PLEISTOCENE? AND LATE PLIOCENE?)**
Mostly poorly stratified, poorly sorted, pebbly sand, but includes some sub-angular bouldery gravel containing huge boulders up to 6 feet (2 meters) in diameter. Clasts are locally derived Precambrian metamorphic rocks and Paleozoic limestone. Some calcite cement is present. A recent water well penetrated a thickness of more than 200 feet (62 meters) of mostly angular, pebbly sand derived from Precambrian gneiss. The surface of this deposit now stands about 200 feet (62 meters) above the modern streams. Interpreted to be younger than QTafd because it contains clasts representative of the present bedrock exposure and it appears to grade to a lower level.
- QTaf **ALLUVIAL FAN DEPOSITS (EARLY PLEISTOCENE AND PLIOCENE?)**
Sub-angular to rounded, poorly to well-sorted, bouldery gravel with varying amounts of silt and clay and some interbeds of silt. Deposited in alluvial fan and

alluvial slope environments (Hawley and Wilson, 1965; Nilsen, 1982; Smith, 2000) by both stream flow and debris flow processes. Surfaces of these deposits are now 80-200 feet (25-62 meters) above modern deposits at several levels that probably represent several different ages. Color is usually dark brown to reddish brown and contrasts with the lighter colored Tsc. Clast lithologies are somewhat representative of adjacent mountains, but generally differ from the nearby younger deposits (Qal, Qaf, Qat). They apparently reflect a different level of bedrock erosion during early Pleistocene and late Tertiary time. From 10 to several hundred feet (3 to 100 meters) thick. Aquifer potential is quite variable and usually unpredictable. Other engineering properties are also quite variable (see below).

- QTafs ALLUVIAL FAN DEPOSITS, STREAM FLOW FACIES (EARLY PLEISTOCENE AND PLEISTOCENE?)
Sub-rounded to rounded, moderately well-sorted, well-stratified, bouldery gravel with interbeds of silt as much as 5 feet (1.5 meters) thick. Gravel was deposited in alluvial fan and alluvial slope environments mainly by stream flow processes. Silt beds show few sedimentary structures, and could be either interbedded loess deposits or overbank deposits. Clast composition in gravels is reflective of nearby bedrock geology, but differs from similar but younger deposits. For example, in the Sypes Creek area, where the best exposures of QTafs are found, clasts within QTafs are mostly limestone, but clasts within younger Qaf and Qafs are mostly Precambrian gneiss. By contrast, nearby older Tsc contains mostly volcanic clasts. The silty beds act as aquitards separating the gravelly layers (Erickson, 1995; Gaston Engineering, 1996; Hay, 1997). The deeper gravelly beds have the potential to be good aquifers, but are laterally discontinuous.
- QTafd ALLUVIAL FAN DEPOSITS, DEBRIS FLOW FACIES (EARLY PLEISTOCENE AND PLEISTOCENE?)
Sub-angular to sub-rounded, poorly sorted, poorly stratified, bouldery gravel, silt, and clay deposited by debris flows. Like all QTaf deposits, clast composition reflects the local bedrock exposures during late Tertiary-early Quaternary time. South of Gallatin Gateway, QTafd contains almost 100% igneous clasts, mostly mafic volcanic rocks, but adjacent Qaf contains abundant limestone and Precambrian gneiss clasts. Usually a poor aquifer, and the large boulders may cause construction and septic system problems.

QTpg

PEDIMENT GRAVEL DEPOSITS (EARLY PLEISTOCENE AND PLIOCENE?)

Well-rounded, moderately sorted, bouldery gravel with sand, silt, and clay. Thickness 0-15 feet (0-5 meters) on dissected, planar sloping surfaces developed mostly on the Sixmile Creek Formation in the Camp Creek Hills area. Clast composition (65% mafic volcanic rocks, 25% Precambrian metamorphic rocks, and 10% sedimentary rocks) mimics that of the conglomerate layers within the Sixmile Creek Formation.. Surfaces stand 150-250 feet (46-77 meters) above modern streams. Mifflin (1963) and Schneider (1970) interpreted these gravels to be Pleistocene, but Pardee (1950) suggested a Pliocene age. The gravels often spill down hills and obscure the underlying geology.

Tsc

SIXMILE CREEK FORMATION (PLIOCENE AND LATE MIOCENE)

Lithology is highly variable, but predominantly light brown to light gray, poorly stratified, poorly sorted, tuffaceous siltstone. Also contains discontinuous and lenticular interbeds of fluvial channel conglomerate, unaltered white volcanic ash, and mudstone. Some beds are cemented by calcite that probably represents caliche. The silt was probably deposited both as eolian loess and as fluvial overbank deposits (Robinson, 1963; Hughes, 1980). The conglomerates are distinctive, being composed of well-rounded, well-sorted cobbles of mostly mafic volcanic rocks even near the base of the Bridger Range where no volcanic bedrock is exposed today. Various sources have been proposed for these cobbles with resulting flow directions of west (Glancy, 1964), east (Robinson, 1963; Mifflin, 1963), south (Hughes, 1980), and northeast (Schneider, 1970). However, it seems likely that the Hyalite (Gallatin/Absaroka) volcanic field to the southeast provided the source. Local bedrock geology contributed some clasts: in the northern part of the map area, Tsc contains up to 30% Proterozoic LaHood clasts, while in the Story Hills, Tsc contains a few percent Livingston Group cobbles. In the fine-grained beds, some thin beds of limestone are present. Hughes (1980) identified some algal and ostracodal limestone, but some limestone may have originated as caliche (Hanneman, 1989). Schneider (1970) studied Tsc (called Madison Valley Formation in his report) in detail in the Madison Bluffs area and found both fluvial and lacustrine environments represented. Unconformities bound the Sixmile Creek Formation, so thickness can be quite variable, but several thousand feet (1000 meters) are probably present in some places.

Douglass (1903) first studied these sediments and named them the Madison Valley beds. Some subsequent workers called them the Madison Valley Formation. Fossil dates (Douglass, 1903; Shultz and Falkenbach, 1949; Dorr, 1956; Glancy, 1964) show a late Miocene to Pliocene age, and an ash bed yielded a K-Ar date of 8.9 M.A. (Hughes, 1980). Therefore, these beds correlate chronostratigraphically, but not lithostratigraphically, with the type Sixmile Creek

Formation (Kuenzi and Fields, 1971; Fields and others, 1985), and we have adopted that name in this study.

Although well-sorted gravel lenses with good aquifer potential exist in parts of the Sixmile Creek Formation, they are unpredictable and often discontinuous. Clayey silt is dominant, so wells drilled in Sixmile Creek Formation are a gamble. Because most wells on the northern “Bozeman Fan” and in the city of Bozeman penetrate Sixmile Creek Formation, its aquifer potential has been intensively studied by Custer and others (1991), who concluded that the groundwater character is unpredictable. Tsc is dominantly fine-grained, which can also severely limit percolation necessary for effective septic systems (Custer and others, 2001).

Landslides occasionally develop in Tsc, but the predominance of silt over clay limits their number. Tsc is usually stable for foundations because it does not contain significant swelling clay, but roads need to be surfaced with gravel or they become impassable when wet.

Tscs	SIXMILE CREEK FORMATION, SILTY FACIES (PLIOCENE AND LATE MIOCENE) Sixmile Creek Formation composed of less than 10% channel gravels. Predominantly poorly sorted silt as described above, but also contains mud and volcanic ash beds. Usually a poor aquifer.
Tscg	SIXMILE CREEK FORMATION, GRAVELLY FACIES (PLIOCENE AND LATE MIOCENE) Sixmile Creek Formation containing 10-50% fluvial channel conglomerate as described above. The remainder consists of fine-grained material, mainly silt.
TAb	BEDROCK (EOCENE THROUGH ARCHEAN) Includes Archean metamorphic rocks, Proterozoic, Paleozoic, and Mesozoic sedimentary rocks, and Eocene intrusive and extrusive volcanic rocks.

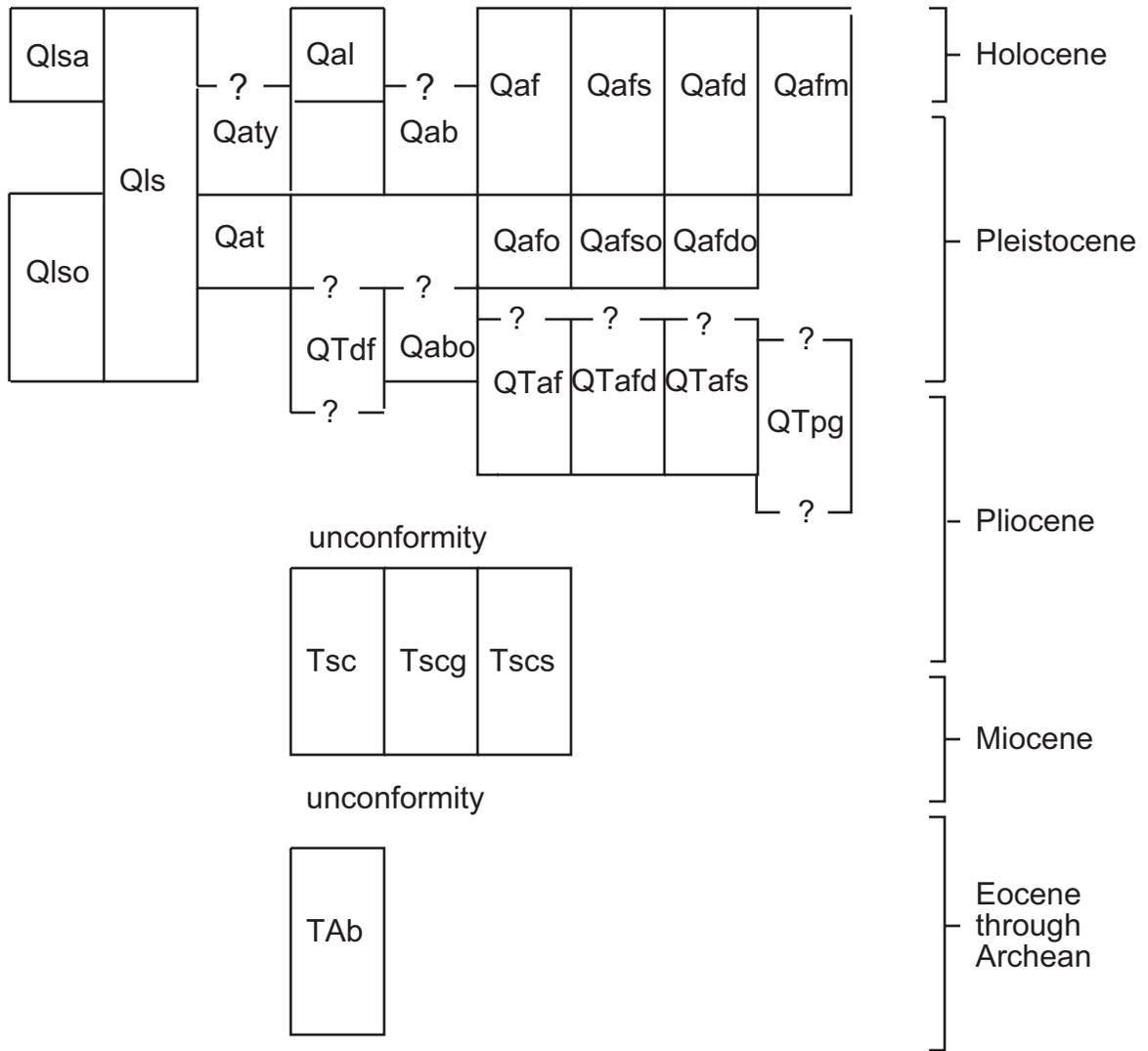


Figure 1. Age correlation chart of map units.

Geologic Summary

Mapping in the Gallatin Valley is especially challenging due to poor exposures and the difficulty in distinguishing lithologic units. Nonetheless, geologists have given the valley considerable attention, beginning with a reconnaissance map by Peale in 1896, followed by fossil reports by Douglass (1903), Schultz and Falkenbach (1949), and Dorr (1956). Later, McMannis (1955), Roberts (1964a,b), and Tysdal (1966) mapped bedrock around the valley margins, while even more time passed before the geology of parts of the valley itself was tackled (Mifflin, 1963; Glancy, 1964; Schneider, 1970; Hughes, 1980). Hackett and others (1960) produced the only comprehensive map of the entire valley. Custer and others (1991) and Custer (1995) reviewed geology of the valley as it relates to groundwater.

More recently, Steve Custer and Bill Locke of the Department of Earth Sciences at Montana State University (MSU), studying the “Bozeman Fan” of Hackett and others (1960), questioned the extent and importance of Quaternary units. Their hypothesis is that the Tertiary Period records significant deposition, while the Quaternary Period has been a time of downcutting and erosion with only minor deposition (Bill Locke, personal communication, 2001). Thus, although Hackett and others (1960) were mostly correct in mapping Quaternary units at the surface, the thicknesses and importance of these units as aquifers are in question. Prompted by rapid population growth and the resulting impacts on the relatively unknown groundwater systems of the Gallatin Valley, the Montana Bureau of Mines and Geology began new geologic mapping of the eastern part of the valley in 2001, hoping for a fresh view. We offer the following summary of our observations and conjectures.

The “Bozeman Fan”, Pediment Surfaces, and Loess

Custer and others (1991) concluded that the northern part of the “Bozeman Fan” (Hackett and others, 1960) is actually an old pediment surface cut on the Sixmile Creek Formation and thinly veneered with Quaternary gravels (Qabo of this report). Like Custer and others (1991), we mapped Sixmile Creek Formation under the MSU campus. We also believe that the Sixmile Creek Formation underlies most of Bozeman and the area of the Bozeman Sanitary Landfill, and crops out in a broad arc a couple of miles (a few kilometers) wide along the toe of the “Bozeman Fan”. These areas of newly recognized Sixmile Creek Formation indicate that the Quaternary has indeed been overstated by previous workers. Drill holes have penetrated 2000 feet (615 meters) of basin fill deposits (Hackett and others, 1960) and gravity data indicate over 6000 feet (1846 meters) in places (Davis and others, 1965; Lageson, 1989), but most of this section is probably composed of Sixmile Creek or underlying Renova Formation. The Tertiary sediments in the Gallatin Valley are fine-grained, which profoundly limits groundwater development (see Custer and others, 1991). Quaternary gravels can be good aquifer hosts, but because many are thin, they are subject to contamination.

Other erosional surfaces carved on Sixmile Creek Formation include the sloping planar

surfaces in the Story Hills (Glancy, 1964) that have been disrupted by faulting, and the now dissected pediment of the southeastern Madison Plateau (also known as the Camp Creek Hills). The origins of other surfaces are less clear. The surface of the Quaternary-Tertiary alluvial fan deposits (QTafs) along the Bridger Range have been interpreted as dissected, loess-covered pediments (Custer, 1995; Erickson, 1995). However, exposures north of Sypes Creek reveal that lithologic contacts within the alluvial fan deposits parallel the surface; in addition, massive silty deposits identical to those interpreted as loess covering a pediment (Custer, 1995; Erickson, 1995) are interbedded with channel and debris flow deposits within the fan. Therefore we suggest that these QTafs surfaces, as well as most other QTaf surfaces, are relict bedding surfaces. The extensive, but sporadic silty surfaces that are so important to Gallatin Valley agriculture are attributed to the preservation of these surficial overbank or loess deposits deposited as part of QTaf units or to the exhumation of silty Sixmile Creek Formation beds.

The lack of consistency and continuity of terraces along the Gallatin River is another enigma. It is difficult to trace terrace surfaces very far or to correlate them downvalley. Mifflin (1963) suggested that ice jams may be responsible for much of the floodplain deposition, leading to discontinuous terraces developed at various levels. Tectonism that affected aggradation and downcutting along the river could offer another explanation.

Unroofing History

Clast lithologies in the Miocene through Holocene units crudely record the uplift history of the Bridger and Gallatin Ranges on the valley margins. The late Miocene and Pliocene Sixmile Creek Formation appears to have been deposited before the present topography existed. Clasts in conglomeratic layers of Sixmile Creek Formation are predominantly rounded mafic volcanic cobbles and include only minor sedimentary rocks. The contrast between Sixmile Creek clast composition and the local bedrock exposures is especially striking along the Bridger Range, where no volcanic bedrock is presently exposed. Furthermore, in the eastern Gallatin Valley, no Sixmile Creek conglomerates are present, even close to the base of the Bridger Range. Apparently the Bridger Range, at least in its present form, did not come into existence until the Pliocene. The source of these Sixmile Creek volcanic cobbles has been the subject of much speculation, but it seems likely that they originated in the Eocene Hyalite (Gallatin/Absaroka) volcanic field to the southeast.

Clasts within younger late Pliocene and early Pleistocene sediments, QTaf, QTafs, and QTafd, appear to record early stages of uplift and erosion of the Gallatin and Bridger Ranges. The clasts were deposited in alluvial fans and alluvial slopes along the mountain fronts, and contain locally derived clasts that are not entirely representative of the modern bedrock exposures. For example, QTafs in the Sypes Canyon area contains almost 100 percent limestone clasts, even though Precambrian metamorphic rocks are extensively exposed today, and nearby, more recent fan deposits (Qaf, Qafs) are comprised mostly of Precambrian metamorphic clasts. A similar situation exists along the Gallatin Range front, where QTaf and QTafd deposits consist of 100 percent mafic volcanic clasts. Nearby bedrock exposures now are mostly Precambrian

metamorphic and Paleozoic sedimentary rocks.

The clast composition of Holocene fans (Qaf, Qafs) contrasts sharply with that of older deposits. Holocene Bridger Range fans contain mostly Precambrian metamorphic clasts. Holocene Gallatin Range fans contain as much as 65 percent Precambrian gneiss and Paleozoic rocks in addition to the mafic volcanic rocks derived from the higher parts of the range.

This approximate unroofing history indicates that the relatively rapid uplift of both the Gallatin and Bridger Ranges is Pliocene and younger.

Geometry of the Valley Bottom and Recent Tectonism

Gravity data (Davis and others, 1965), the presence of near-surface Precambrian bedrock encountered during construction on the Montana State University campus, closely spaced intersecting faults mapped along the valley margins (McMannis, 1955; Roberts, 1964a,b; Tysdal, 1966), and widely varying fault plane solutions from recent Gallatin Valley earthquakes (Stickney, 1997; Stickney and Lageson, 1999) all suggest that the valley floor may be broken into a complex arrangement of blocks. Some faults extend into the sedimentary cover, as seen in (1) Sixmile Creek Formation outcrops along Church Street (Fix, 1940; Glancy 1964), (2) photo-linears in QTaf and Tsc, and (3) offset QTaf surfaces in the southern valley (this study). Gentle folds seen in Sixmile Creek Formation beds distal to the mountain fronts may represent the near-surface expression of buried faults. Sixmile Creek Formation has also been tilted toward both the Bridger and Gallatin Ranges by listric normal faults as suggested by bedding attitudes proximal to the range front faults.

Although we found no Holocene fault scarps, the valley is seismically active (Stickney, 1997; Stickney and Lageson, 1999). Thickness variations also support Quaternary tectonism. Most Quaternary deposits are less than 100 feet (31 meters) thick, but in the Belgrade area drill holes have encountered 800 feet (246 meters) of Quaternary gravels (Hackett and others, 1960). The modern Gallatin River exits the valley near Logan, Montana, through a bedrock constriction containing less than 40 feet of Quaternary gravel. This contrast in alluvial thickness suggests that the thick Quaternary alluvium filled an actively subsiding structural trough, perhaps bounded by faults extending northeast from the Bozeman Hot Springs area (Donovan and others, 1982) and by the Central Park Fault, the western extension of the Pass Creek Fault (Hackett and others, 1960; Lageson, 1989).

Cross-Section A-A'

Cross-section A-A' extends down the length of the "Bozeman Fan" (Hackett and others, 1960) and was interpreted with the aid of gravity data (Davis and others, 1965) and stratigraphic information from Custer and others (1991). The Bozeman Fan is actually composed of two superimposed landforms, the Hyalite Alluvial Fan and a pediment surface. The Hyalite Fan (Qafso) was deposited on thin alluvial deposits (Qabo), which in turn overlie a pediment surface

cut on Sixmile Creek Formation. The Sixmile Creek Formation was gently folded, as illustrated by the dotted lines, and faulted prior to deposition of the overlying, unconformable Quaternary deposits. Continued movement on some faults during the Quaternary formed the Belgrade structural trough, filled with Quaternary gravel, on the northwest end of the cross-section. Note the listric normal fault bounding the Gallatin Range, the rotation of Sixmile Creek beds, and the concealed antithetic fault indicated by gravity data (Davis and others, 1965) immediately to the northwest.

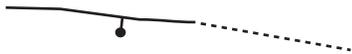
Map Symbols



Contact; dashed where approximate



Fault; dotted where concealed; relative sense of displacement shown where known.



Normal fault; ball and bar on downthrown side; dotted where concealed.



Strike slip fault; dotted where concealed



Inferred fault, interpreted using drill hole data, gravity data, or air photos includes faults that are concealed.



Strike and dip of bedding

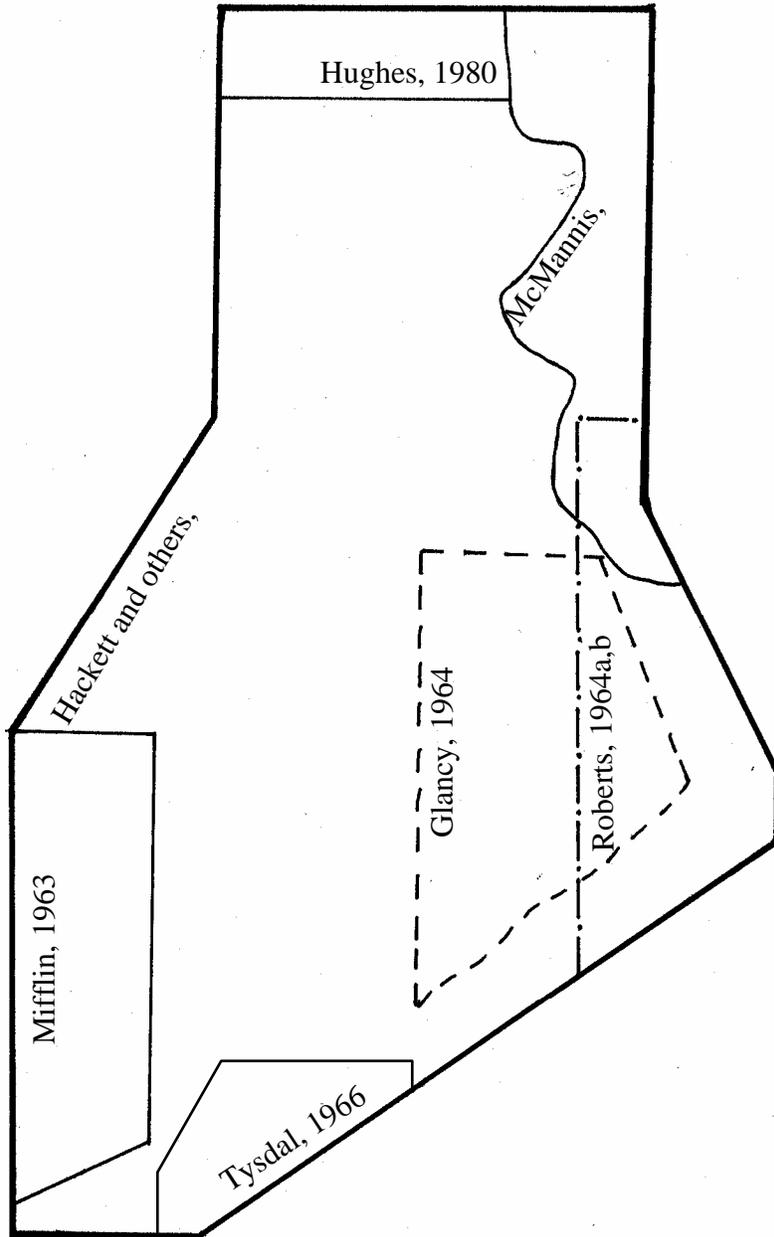


Figure 2. Index to previous mapping in the eastern Gallatin Valley.

References Cited

- Custer, S.G., Christner, C., Dixon, S., Wright, A., Burton, G., Snyder, R., Aspinall, R., Rupp, G., and Roark, T., 2001, Spatial data for septic assessment: unpublished report available on the web at <http://mapserver.giac.montana.edu/maps/319a/lwqdsepx.html>.
- Custer, S.G., Donohue, D., Tanz, G., Nichols, T., Sill, W., Wideman, C., 1991, Groundwater potential in the Bozeman Fan subarea, Gallatin County, Montana: unpublished report to Water Development Bureau, Montana Department of Natural Resources and Conservation, 118 p.
- Custer, S.G., 1995, A walking tour of the geology of the southeastern Gallatin Valley, *in* Field Trip Guidebook: Self Guided Field Trips near Bozeman: Montana State University Department of Earth Sciences in conjunction with 1995 Rocky Mountain Section Meeting, Geological Society of America, p. 1-12.
- Davis, W.E., Kinoshita, W.T., and Robinson, G.D., 1965, Bouger gravity, aeromagnetic, and generalized geologic map of the eastern part of the Three Forks Basin, Broadwater, Madison, and Gallatin Counties, Montana: U.S. Geophysical Investigations Map GP 498, 5 p., scale 1:62,500.
- Donovan, J.J., Stickney, M.C., and Sonderegger, J.L., 1982, Subsurface investigations at Bozeman Hot Springs: Geological Society of America Abstracts with Programs, v. 14, no. 6, p. 310.
- Dorr, J.A., Jr., 1956, Anceney local mammal fauna, latest Miocene, Madison Valley Formation: *Journal of Paleontology*, v. 3, p. 62-74.
- Douglass, Earl, 1903, New vertebrates from the Montana Tertiary: *Carnegie Museum Annals*, Pittsburgh, v. 5, p. 159-165.
- Erickson, E.J., 1995, Water-resource evaluation and groundwater-flow model for Sypes Canyon, Gallatin County, Montana: Butte, Montana Tech, M.S. thesis, 69 p.
- Fields, R.W., Tabrum, A.R., Rasmussen, D.L., and Nichols, R., 1985, Cenozoic rocks of the intermontane basins of western Montana and eastern Idaho: A summary, *in* Flores, R.M., and Kaplan, S.S., eds., *Cenozoic paleogeography of the west-central United States*: Society of Economic Paleontologists and Mineralogists, p. 9-36.
- Fix, P.F., 1940, Structure of the Gallatin Valley, Montana: Boulder, University of Colorado, Ph.D. dissertation, 68 p.

- Gaston Engineering, 1996, Engineer's report for the aquifer testing at the Spirit Hills subdivision, Bozeman, Montana: unpublished report, 9 p.
- Glancy, P.A., 1964, Cenozoic geology of the southeastern part of the Gallatin Valley, Montana: Bozeman, Montana State University, M.S. thesis, 66 p., map scale 1:24,000.
- Griffith, E.F., 1982, Environmental geology of the southeast margin of the Gallatin Valley, Gallatin County, Montana: Bozeman, Montana State University, M.S. thesis, 106 p., map scale 1:24,000.
- Hackett, O.M., Visher, F.N., McMurtrey, R.G., and Steinholber, W.L., 1960, Geology and groundwater resources of the Gallatin Valley, Gallatin County, Montana: U.S. Geological Survey Water-Supply Paper 1482, 282 p., map scale 1:63,360.
- Hanneman, D.L., 1989, Cenozoic basin evolution in part of southwestern Montana: Missoula, University of Montana, Ph.D. dissertation, 374 p.
- Hay, J.E., 1997, An investigation of groundwater recharge along the western flank of the southern Bridger Range, southwestern Montana: Bozeman, Montana State University, M.S. thesis, 56 p.
- Hawley, J.W., and Wilson, W.E., 1965, Quaternary geology of the Winnemucca area, Nevada: University of Nevada, Desert Research Institute Technical Report 5, 66 p.
- Hughes, G.C., 1980, Cenozoic geology and geomorphology of the Dry Creek Valley, Gallatin County, Montana: Bozeman, Montana State University, M.S. thesis, 146 p.
- Kuenzi, W.D., and Fields, R.W., 1971, Tertiary stratigraphy, structure, and geologic history of the Jefferson Basin, Montana: Geological Society of America Bulletin, v. 82, p. 3373-3394.
- Lageson, D.R., 1989, Reactivation of a Proterozoic continental margin, Bridger Range, southwestern Montana, *in* French, D.E., and Grabb, R.F., eds., Geologic Resources of Montana, Montana Centennial Edition, Volume 1: Montana Geological Society 1989 Field Conference Guidebook, p. 279-298.
- McMannis, W.J., 1955, Geology of the Bridger Range, Montana: Geological Society of America Bulletin, v. 66, p. 1385-1430.
- Mifflin, M.D., 1963, Geology of a part of the southern margin of the Gallatin Valley, southwest Montana: Bozeman, Montana State University, M.S. thesis, 111 p., map scale 1:24,000.

- Nilson, Tor H., 1982, Alluvial fan deposits, *in* Scholle, P.A., and Spearing, D., eds., Sandstone Depositional Environments: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 49-86.
- Pardee, J. T., 1950, Late Cenozoic block faulting in western Montana: Geological Society of America Bulletin, v. 61, p. 359-406.
- Peale, A.C., 1896, Description of the Three Forks sheet (Montana): U.S. Geological Survey Geologic Folio GF-24, 5 p., map scale 1:250,000.
- Roberts, A. E., 1964a, Geologic map of the Mystic Lake [renamed Mount Ellis] quadrangle, U.S. Geological Survey Miscellaneous Geological Investigations Map I-398, scale 1:24,000.
- Roberts, A. E., 1964b, Geologic map of the Fort Ellis [renamed Kelly Creek] quadrangle, U.S. Geological Survey Miscellaneous Geological Investigations Map I-397, scale 1:24,000.
- Robinson, G. D., 1963, Geology of the Three Forks quadrangle, U.S. Geological Survey Professional Paper 370, 143 p.
- Schneider, G.B., 1970, Cenozoic geology of the Madison Bluffs area, Gallatin County, Montana: Bozeman, Montana State University, M.S. thesis, 61 p.
- Schultz, C.B., and Falkenbach, C.H., 1949, *Promerycochaesinae*, a new subfamily of oreodonts: American Museum of Natural History Bulletin, v. 93, p. 69-198.
- Smith, G.A., 2000, Recognition and significance of streamflow-dominated piedmont facies in extensional basins: Basin Research, v. 12, p. 399-412.
- Stickney, M.C., 1997, Seismic source zones in southwest Montana: Montana Bureau of Mines and Geology Open-File Report MBMG 366, 48 p.
- Stickney, M.C., and Lageson, D.R., 1999, The Nov. 6, 1997 M 3.7 Belgrade, MT earthquake: Unusual aspects and their implications to regional seismicity: Geological Society of America 1997 Rocky Mountain Section meeting, Pocatello, Idaho, Abstracts with Programs, p. A-57.
- Tysdal, R.G., 1966, Geology of a part of the north end of the Gallatin Range, Gallatin County, Montana: Bozeman, Montana State University, M.S. thesis, 95 p., map scale 1:24,000.

