Friends of the Pleistocene ☸ Rocky Mountain Cell
Field Conference Guidebook

Late Pleistocene - Holocene Evolution *of the* Northeastern Yellowstone Landscape

1995

Grant A. Meyer, editor

Road Log and Mini-Papers

Highway 212: Northeast Entrance Road, Yellowstone National Park
Colter Pass to Lamar Ranger Station

Introduction

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LATE PLEISTOCENE-HOLOCENE GEOLOGIC STUDIES IN NORTHEASTERN YELLOWSTONE

The 1995 Rocky Mountain Friends of the Pleistocene Field Conference focuses on the area in and around the northeastern corner of Yellowstone National Park. This rugged mountain landscape has been the scene of major landscape-forming activity, not only during extensive Pinedale glaciation, but throughout the postglacial period as well, providing a great natural laboratory for the study of environmental change. An added benefit for Quaternary scientists is the relatively undisturbed natural state of the Yellowstone landscape, which allows clear views unhindered by major development, preserves key geomorphic and stratigraphic records, and allows for more accurate analogies to be drawn between modern process and prehistoric events. We would like to thank those individuals with the foresight to preserve this unique area by creation of Yellowstone National Park in 1872.

The work of Kenneth L. Pierce on glaciation in northern Yellowstone (Pierce, 1979, and this volume) has provided a fundamental understanding of late Pleistocene history and processes in the field trip area. Continuing work by Ken Pierce and that of William W. Locke (this volume) continues to refine our knowledge of icecap glaciation and events during the transition from icecap glaciation, through mountain valley glaciers, to deglaciation. Studies of postglacial alluvial fan and fluvial processes and history in northeastern Yellowstone formed the PhD work of Grant A. Meyer with Steve Wells at University of New Mexico (Meyer, 1993a); these studies are augmented by subsequent work with undergraduate students Jim Anderson, Matt Bingham, Eric Simpson, and Peter O'Hara at Middlebury College. A specific focus of this research is on the role of forest fires in alluvial processes and the relation of fire and alluvial chronology to climatic history in Yellowstone (Meyer et al., 1992, 1995, and this volume). Palynological and paleoclimatic studies by Cathy Whitlock and Pat Bartlein (1993, and this volume) and students at University of Oregon provide a framework for understanding late-Pleistocene through Holocene paleoenvironments in the field trip area. The dynamic alluvial processes of northeastern Yellowstone are relevant to current environmental problems, as shown by the work of Andrew Marcus (with graduate students Julie Stoughton and Scott Ladd at Montana State University, this volume) and Grant Meyer on transport of mine tailings and associated heavy metals in the Soda Butte Creek system.

OVERVIEW OF LATE CENOZOIC GEOLOGIC EVOLUTION

Yellowstone National Park lies at the center of a high topographic anomaly that is 350-400 km in diameter (Suppe et al., 1975; Smith et al., 1985). This large elevated area may be the lithospheric expression of a major mantle plume or "hotspot" (Anders et al., 1989; Pierce and Morgan, 1992; Smith and Braile, 1993). According to the hotspot model, the North American plate has migrated southwestward over the plume for the last 16 million years, producing a trail of bimodal volcanism from the Idaho-Oregon-Nevada border area, along the eastern Snake River Plain, to the current area of activity in Yellowstone. Large-volume silicic volcanic activity began in the Yellowstone area about 2.0 Ma with eruption of the Huckleberry Ridge Tuff and formation of one of the world's largest known calderas. Major caldera eruptions followed at about 1.3 Ma and 0.6 Ma, the latter forming the Yellowstone caldera (Christiansen, 1984). Rapid regional uplift likely accompanied major hotspot-related volcanism, and uplift may be continuing at present in the Yellowstone region (Reilinger, 1985). Although the high rates of normal faulting that are associated with the Yellowstone hotspot (e.g., Anders et al., 1989) have generated high relief in adjacent areas, for example, the Teton Range (e.g., Smith et al., 1993), and the upper Yellowstone Valley north of Yellowstone (e.g., Personius, 1982), no major offsets have accumulated in northeastern Yellowstone.

Accelerated late Neogene regional uplift in the Yellowstone region, however, has probably driven the development of substantial relief where highly erodible rocks are present (e.g., Pierce and Morgan, 1992). The Absaroka Range along the eastern boundary of Yellowstone National Park is notable among these mountainous areas, being composed largely of poorly indurated, andesitic volcaniclastic rocks of the Absaroka Volcanic Supergroup (e.g., Prostka et al., 1975b). Summits in the Absaroka Range commonly consist of broad low-relief plateaus which are accordant in elevation, suggesting a relict geomorphic surface, or set of surfaces (Pierce and Morgan, 1992). These upland surfaces are poorly preserved in northeastern Yellowstone relative to areas to the south and east. Summit plateaus, however, are evident on Mount Hornaday, Abiathar Peak, and a number of other peaks in this area. The ages of these inferred geomorphic surfaces are poorly known. A basalt flow overlying a high-elevation surface predates major canyon incision in the southern Absaroka Range, and has been dated at 3.6 Ma (Ketner et al., 1966; Blackstone, 1966). A gravel on the Absaroka Range summit plateau south of Yellowstone National Park contains obsidian clasts K-Ar-dated at about 6.3 Ma. The location of the gravel relative to obsidian sources suggests deep canyon cutting in the range since deposition (Pierce and Morgan, 1992). These observations support the hypothesis that broad-scale uplift has driven the generation of major relief in northeastern Yellowstone in Pliocene and Quaternary time.

The Yellowstone Plateau has a general elevation of about 2500 m. The Beartooth Mountains to the north and northeast consist of a higher plateau formed on a large, Archean basement-cored Laramide foreland uplift. These high plateaus precipitated the development of large icecaps during glacial stages of the Pleistocene (Pierce, 1979; Locke, this volume). During at least some phases of glaciation, the Soda Butte and Slough Creek valleys served as major conduits for Beartooth Uplift ice. These ice streams eroded deep trough valleys in the friable Eocene rocks and underlying Paleozoic sediments (Fig. 1). Peaks of the Absaroka Range in this area rise to over 3300 m, and local relief of 800-1000 m in 1.2-2.0 km is present. Mountain sides average 25-40˚ from peak to valley bottom, and many slopes have extensive cliff faces and bare bedrock.

Bedrock underlying the steep upper slopes of the Soda Butte and Slough Creek valleys consists mainly of (1) andesitic and minor basaltic volcaniclastic rocks and lava flows of the Eocene Wapiti and Mt. Wallace Formations of the Sunlight Group; and (2) the Lamar River Formation of the Washburn Group, which is dominated by andesitic volcaniclastic rocks, including abundant laharic sediments (Prostka et al., 1975a, 1975b) (Fig. 1). Although these units are listed in descending order, complex erosional and interfingering relations exist between them. Some small intermediate to felsic intrusive bodies of Eocene age are present in the upper Soda Butte Creek and Slough Creek drainages (Wedow et al., 1975; Elliot, 1979).

The Eocene volcanic and volcaniclastic rocks overlie an unconformity of significant relief (Fig. 1). In northeastern Yellowstone, this surface was generally eroded to the stratigraphic level of the lower Madison Group (i.e., the Mississippian Lodgepole Limestone), which forms cliff bands along lower valley walls. Carbonate sedimentary rocks are also abundant in the rest of lower Paleozoic section, which consists of the Devonian Three Forks and Jefferson Formations (shale and carbonate rocks), the Ordovician Bighorn Dolomite, and the Cambrian Snowy Range Formation (shales), Pilgrim Limestone, Park Shale, Meagher Limestone, Wolsey Shale, and Flathead Sandstone. The Bighorn Dolomite and Pilgrim Limestone are prominent cliff-forming units. The Paleozoic rocks have an overall dip to the southwest, away from the Beartooth Uplift. The unconformity on the Lodgepole Limestone disappears beneath the surface in the lower Lamar Valley area, and Paleozoic rocks are not exposed in the upper Lamar drainage above the Soda Butte Creek confluence.

Granitic gneisses and lesser amphibolites of Archean age underlie the Paleozoic section in the northeastern Yellowstone area and are extensively exposed on the Beartooth Uplift, the major source area for Pleistocene ice in northeastern Yellowstone. Within present stream drainages, these rocks crop out only in uppermost Soda Butte Creek, but are widely exposed in the upper Slough Creek drainage north of the park boundary. They are also exposed on structural highs in the lower Slough Creek and Lamar Canyon area, where granitic gneisses form erosionally resistant knobs, narrow gorges, and knickpoints along the valley bottom.

Late Pleistocene glacial history and geomorphic development

Reconstructions of the Pinedale full-glacial ice mass (about 20-30 ka) in northeastern Yellowstone imply that ice was about 3600-3800 feet (1100-1200 m) thick along the Soda Butte Creek and Slough Creek valleys. Only the highest peaks in this area were emergent, for example, Abiathar Peak (10,928 ft), Amphitheater Peak (11,042 ft), and Cutoff Mountain (10,695 ft) (Pierce, 1979). Pierce (1979) concluded that this flow was part of a larger mountain icecap generated on the Beartooth Uplift and covering all but the highest peaks. The full-glacial flow from this mountain icecap abutted an icecap on the Yellowstone Plateau, enhancing the thickness of both icecaps. The reconstructed full-glacial flow line that traversed the Soda Butte valley was about 145 km long, originating about 12 km north-northeast of Cooke City and extending to the Pinedale glacial terminus in the Yellowstone valley 57 km downstream from Gardiner, Montana (Pierce, 1979, Plates 1 and 4). Locke (this volume) presents an alternate reconstruction that places an ice divide within the Soda Butte valley, with ice draining to both the Yellowstone and Clarks Fork termini. The effects of the thick full-glacial flow were largely erosional in the Soda Butte valley, and most till appears to relate to later, less extensive phases of Pinedale glaciation.

During late Pinedale recession, icecaps on the Yellowstone Plateau downwasted rapidly, whereas ice drainage continued from the Beartooth Uplift. Stillstands during retreat of the main outlet terminus occurred near the North Entrance of the Yellowstone National Park (Deckard Flats) and near the Yellowstone-Lamar River confluence (Junction Butte). Ice thicknesses in Soda Butte Creek and Slough Creek at these times were about 2500-3000 ft (750-900 m) and 1000-2000 ft (300-600 m), respectively, with increasingly channelized ice flow along these major trough valleys (Pierce, 1979). Thick sequences of lacustrine sand and silt provide evidence for an ice-dammed lake in the upper Lamar River drainage above the Soda Butte confluence at Junction Butte time, and suggest that deglaciation of the relatively low-elevation upper Lamar drainage preceded ice retreat in Soda Butte Creek (Pierce, 1974a). Similarly, the Soda Butte glacier appears to have retreated from the lower Lamar Valley prior to retreat of the Slough Creek lobe (Pierce, 1979), thus an ice-dammed lake probably existed in the lower Lamar Valley (see road log, Stop 20).

Minor sets of recessional moraines occur upvalley of the Junction Butte moraines in the Elk Tongue area of Slough Creek, and in the Trout Lake area of lower Soda Butte Creek (Meyer, 1993a). Near Trout Lake, moraines appear to be complexly intermingled with a large landslide that originates in a 2.5 km-wide bowl-shaped headscarp in volcaniclastic rocks on Mount Hornaday. As suggested by Pierce (1974a), the Trout Lake landslide may have been at least in part emplaced onto and against stagnant ice (see road log, Stop 14).

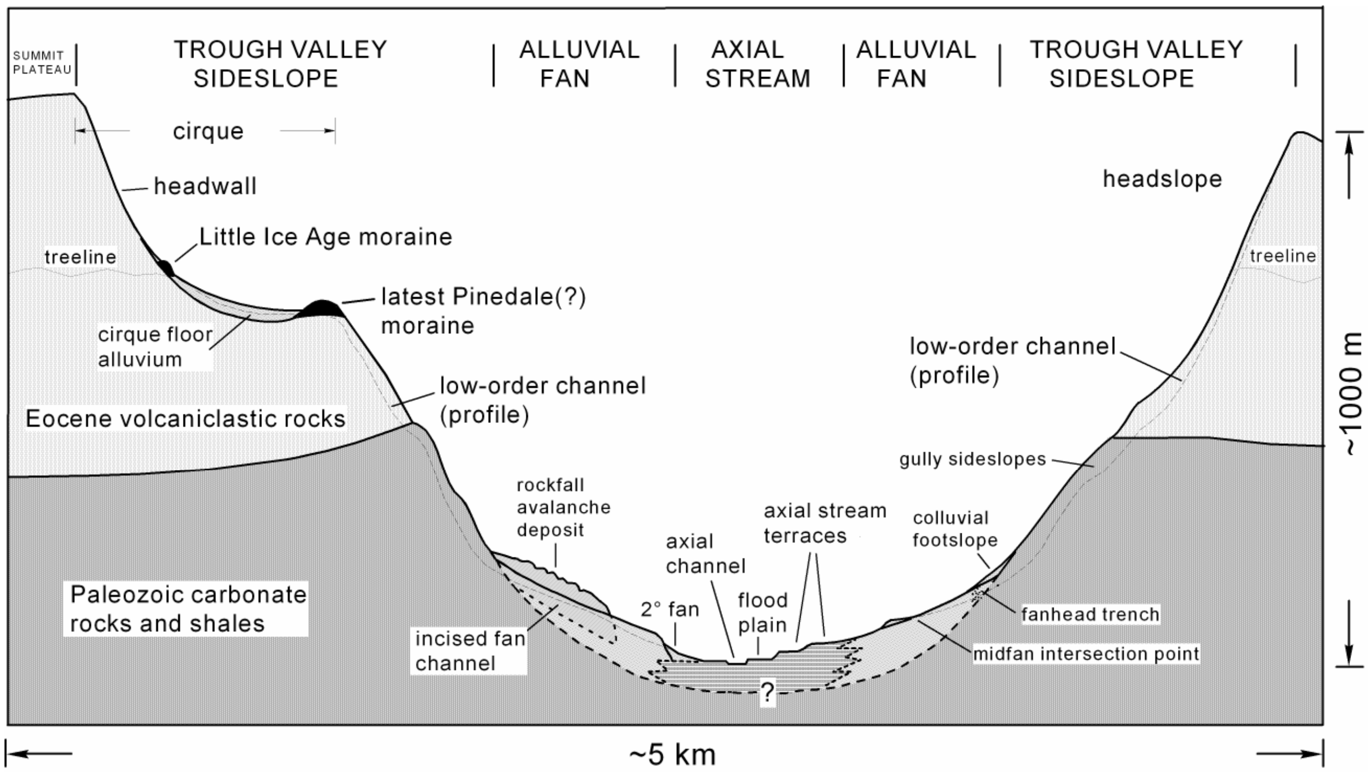

Figure 1. Diagrammatic cross-sectional sketch of a northeastern Yellowstone glacial trough valley showing primary (capital letters) and secondary geomorphic elements of the Holocene sediment transport and storage system. Simplified bedrock geology is also shown.

As a further complication, the landslide may also have involved till emplaced in the headscarp area during Pinedale glaciation. Possible outwash deposits from a terminus in this area are found south and east of Trout Lake, but are disrupted by later slumping and are not traceable further downstream.

The Soda Butte trunk glacier had its source in a broad upland basin on the Beartooth Uplift gneisses that lies between 9850 and 11,800 feet (3000-3600 m) in elevation (Pierce, 1979). Retreat of ice from the lower-elevation Amphitheater and Pebble Creek drainages probably preceded retreat in the main Soda Butte drainage, because granitic-gneiss erratics are found the lower Amphitheater Creek drainage, and lacustrine deposits of probable late Pinedale age are found in both the Amphitheater and Pebble Creek drainages (Pierce, 1974a, 1979). Moraines originally mapped as Neoglacial but now thought to be of latest Pinedale age exist in high cirques below Amphitheater and Abiathar Peaks in the upper Soda Butte drainage ("Temple Lake" moraines of Pierce, 1974a). Erratics of Beartooth gneiss found just below these moraines suggest that these small local cirque glaciers coexisted with, or were regenerated after, a 1300-ft (400-m) thick Soda Butte trunk glacier (Pierce, 1974a, 1979).

As deglaciation progressed, oversteepened bedrock and lateral moraines along the Soda Butte Creek and Slough Creek trough walls became unsupported by ice, thus highly unstable. Many large rockfall and debris avalanches (such as the Trout Lake landslide) are thought to have occurred at this time (e.g., Pierce, 1974a). Some large landslides, however, are demonstrably younger, such as the Foster Lake landslide in the lower Soda Butte valley (see also road log Stop 6). Thick alluvial deposits forming benches well above Holocene alluvial surfaces are common features along upper Lamar River tributaries and parts of the Amphitheater and Pebble Creek drainages. Pierce (1974a) mapped the deposits associated with these high-level fan and terrace features as kame sediments, and suggested that they were deposited in response to higher base levels associated with nearby ice.

Postglacial geomorphic and tectonic activity

Postglacial geomorphic activity in northeastern Yellowstone has involved (1) weathering, erosion, and colluviation on slopes (although accumulation of colluvium has been minor on many steep slopes); (2) construction of alluvial fans along trough valley sides by tributary streams; (3) axial-stream sediment transport, including erosion and redistribution of glacial sediments; (4) mass movements ranging from small slumps and earthflows to major debris avalanches; and (5) cirque glaciation (Fig. 1). If the older cirque moraines mapped as Temple Lake by Pierce (1974a) are of latest Pinedale age, as seems probable, Holocene glaciation in the Lamar River drainage is limited to the growth of small ice masses in well-shaded north-facing cirques at the base of steep headwalls, e.g. below Amphitheater Peak. The age of this youngest, very limited glacial advance has not been established locally. The steep distal slopes, sharp crests, and sparsely vegetated nature of the associated end moraines (mapped as "Gannett Peak" till by Pierce, 1974a), however, suggest that they correlate with Little Ice Age moraines formed sometime between ca. 1300 and 1900 AD (cf. Davis, 1988).

The 33 km-long curvilinear Lamar River valley has long suggested a fault lineament (e.g., Love, 1961), but evidence for significant stratigraphic offset across the valley has not been found (e.g., Prostka et al., 1975a, 1975b). Short lineaments within latest Pinedale glaciofluvial deposits parallel the Lamar Valley above the Soda Butte Creek confluence (Pierce, 1974a). Surface offset along these lineaments, however, has been very small. Examination of the southwest margin of the Lamar Valley by K.L. Pierce and G.A. Meyer in 1991 revealed no clear evidence of postglacial surface rupture. A possible exception exists in local graben-like faulting just below the Cache Creek confluence (Pierce, 1974a). Broad-scale contemporary uplift of 3-4 mm/yr has been documented in the Yellowstone region (Holdahl and Dzurisin, 1991) and may be long-continued. Regional uplift may have accelerated incision rates of streams in the northeastern Yellowstone area over the middle to late Pleistocene (Pierce and Morgan, 1992). Also, isostatic rebound accompanying and following downwasting of the Yellowstone icecap probably occurred over late Pinedale and early postglacial time. These broad-scale deformation mechanisms may be involved in driving long-term incision in northeastern Yellowstone alluvial systems, but are unlikely to be responsible for Holocene fluctuations in the behavior of these systems.

Paraglacial influences on geomorphic and alluvial activity

Glacial landforms and deposits often exist in marked disequilibrium with the deglacial and postglacial environment, especially in mountainous terrain. Erosion and sedimentation promoted by this disequilibrium have been termed "paraglacial" processes (Ryder, 1971; Church and Ryder, 1972; Church and Slaymaker, 1989). Major Quaternary glacial cycles which condition the landscape for paraglacial processes occur on a 10^4-10^5 yr timescale, and relaxation time (cf. Bull, 1991) required to reach a new dynamic equilibrium after glacial perturbation may be of equally great length in mountain landscapes.

During interglacial episodes such as the Holocene, however, changes in the rate at which these processes operate may be driven by shorter-term climatic fluctuations. In northeastern Yellowstone, erosion of steep glacial trough walls and aggradation of alluvial fans along their base is an ongoing adjustment of valley form to the replacement of ice drainage by stream drainage. Pierce (1974a) mapped a large proportion of the alluvial fan surfaces as latest Pinedale in age, in part on the assumption of maximum paraglacial fan construction rates immediately following deglaciation, and designated fan segments with clear evidence of recent activity as Holocene (K.L. Pierce, oral communication, 1989). Recent ^{14}C dating of alluvial fans, however, shows that the majority of fan surfaces are of middle to late Holocene age (Meyer et al., 1995).

In a study of sediment yield from modern river basins in British Columbia, Church and Slaymaker (1989) inferred that remobilization of glacial sediment predominated over primary denudation of the landscape. Rivers in that continental-glaciated region have large volumes of unstable glacial sediment stored along their channels. Although remobilization of glacial sediments is locally quite active in northeastern Yellowstone, less glacial sediment remains stored in the steep valleys, and mantles of till are found mostly in more stable lower slope positions along valley walls. Primary denudation is very active in erosion of the friable bedrock of glacial trough walls, although this process may be considered paraglacial as well. Relatively narrow and discontinuous outwash and kame terraces along the Soda Butte and Slough Creek valleys imply that the majority of the primary glacial sediments have already been removed by fluvial erosion or buried by alluvial fan deposition. The upper Lamar River drainage, however, still contains a large volume of lacustrine and alluvial sediment emplaced during ice-stagnation and ice-damming episodes, and streams are locally undercutting and removing that material.

MODERN CLIMATE AND VEGETATION

Yellowstone National Park lies in a high-elevation, interior continental area influenced by air masses from the Pacific Ocean, Arctic regions, and to a much lesser extent, the Gulf of Mexico. The park is affected by southward excursions of the polar front in winter, when storms bring moisture predominantly from the North Pacific via the relatively low Columbia River Plateau and Snake River Plain. The higher elevation areas of the park receive the majority of their precipitation during winter, and 75 to 85% of the total precipitation falls as snow, or as rain on snow (Despain, 1987). Very cold and dry continental air masses often extend into Yellowstone from the western Great Plains in December through February. Some spring precipitation may be derived from moist subtropical Pacific air masses, although the majority of these storms do not reach further north than the Utah-Idaho border (cf. Redmond and Koch, 1991). The lower-elevation Yellowstone, Lamar, and Soda Butte valleys lie in the rain-shadow of the Yellowstone Plateau and are much drier. These areas have late-spring peaks in precipitation and receive 35 to 55% of their precipitation as rain (Despain, 1987). Summer moisture is derived more often from localized convective storms than from large frontal systems, and is part of the general monsoonal flow (Whitlock and Bartlein, 1993). Although the high-elevation areas of Yellowstone catch more thunderstorm rainfall because of orographic effects, monsoonal precipitation is of greater relative importance in the lower valleys because of their dry winters.

A strong moisture gradient exists in northeastern Yellowstone, where precipitation (and the proportion of snowfall) increases with elevation. Average annual precipitation increases from about 360 mm at Lamar

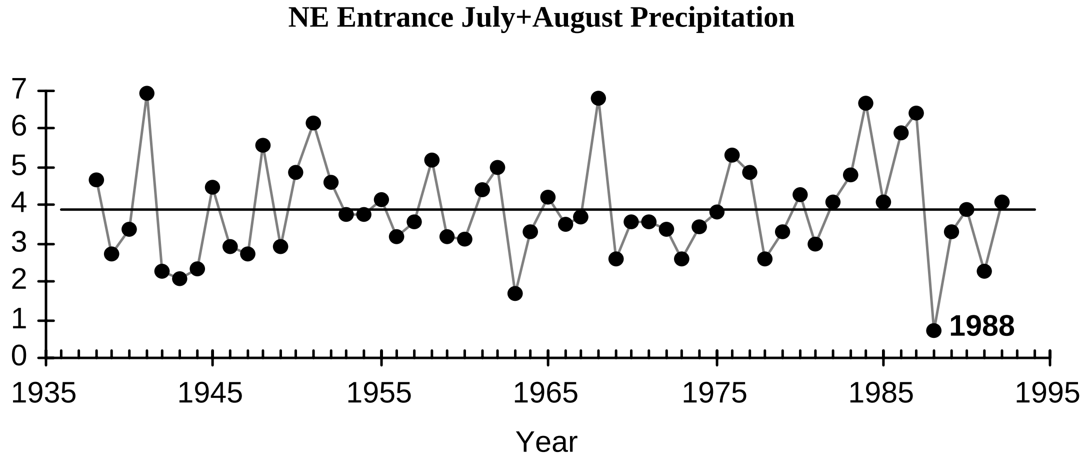

Figure 2. Variations in July and August precipitation totals for 1938-1992 at the Northeast Entrance Station of Yellowstone, plotted around the average for the period. The severe 1988 summer drought followed several years of above average precipitation.

Ranger Station (2000 m or 6560 ft) to 660 mm at Cooke City (2302 m or 7553 ft), and continues to increase up the mountain slopes, with ~800 mm at 2450 m (8000 ft) to as much as 1300 mm at 3050 m (10,000 ft) along the eastern park boundary (Dirks and Martner, 1982).

Average annual temperatures in northeastern Yellowstone range downwards from about 1.8˚C at Lamar Ranger Station. Monthly mean temperatures are well below freezing in November through March at Lamar R.S., and adiabatic lapse rates of about 5.3 to 9.8˚C per 1000 m of elevation (Despain, 1987) imply that monthly mean temperatures may remain below freezing from October to June at upper elevations. Summer temperatures are moderated by elevation and rarely exceed 32˚C; average daily maximums range from 20 to 26˚C for the summer months at Lamar R.S. (Dirks and Martner, 1982). Although the climate is generally cool, both winter and summer precipitation are quite variable, and extreme summer droughts occasionally develop (Balling et al., 1992b). Extreme drought combined with high winds allowed wildfires to burn over large areas in July and August of 1988.

Climatic gradients are strongly reflected in vegetation patterns in northeastern Yellowstone. The lower Lamar and Soda Butte valleys are dominated by dry grasslands and big sagebrush (*Artemisia tridentata*) - bunchgrass steppe communities, with moist meadows in some broad floodplain areas. Mixed Douglas fir (*Pseudotsuga menziesii*) and grassland along the footslopes of the lower valleys are transitional to open stands of Douglas fir (which extend higher on south aspects). These stands are in turn transitional to more closely-growing mixed-conifer communities, often dominated by lodgepole pine (*Pinus contorta*), but also containing Douglas fir, subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*). Lodgepole-dominated stands of mixed conifers comprise the majority of the forest area in northeastern Yellowstone and, in mature stages, are highly susceptible to crown fires (Romme and Despain, 1989; Barrett, 1994). Smaller, more mesic meadows are found at middle elevations on lower alluvial fans, moraines, and broad ridge crests, particularly on south aspects. Near upper treeline (at ca. 2750-3050 m), subalpine fir and whitebark pine (*Pinus albicaulis*) are the main conifers.

FOREST FIRES IN YELLOWSTONE

The 1988 fires

The great complex of fires that spread over the Greater Yellowstone area in 1988 were by far the largest such event recorded in that area, and one of major ecological and geomorphic significance (e.g., Christensen, 1989; Meyer et al., 1992). Drought was present in the Greater Yellowstone area in the winter of 1987-88, and was considered severe by mid-May (USDA/USDI, 1988). A preceding series of wet summers (Fig. 2) led some fire managers to believe that the drought would be broken by rains in July and August (Schullery, 1989). Almost no rain fell in the park during these months, however, and Figure 2 shows that high year-to-year variability in summer precipitation is expectable, precluding predictions based on short-term trends.

The first fire of the 1988 season was started by lightning on June 23 in the backcountry near Shoshone Lake (Fig. 3) (Carey and Carey, 1989). By mid-July, it was apparent that an unusually severe drought and fire season was developing, and Park Service managers decided that all existing and subsequent fires would be suppressed to the greatest practical extent. At this time, only about 1% of the total 1988 burn area of 562,310 ha had burned in the greater Yellowstone area (Schullery, 1989) (Fig. 3). Although the eight major fire complexes that developed in 1988 centered on Yellowstone National Park, the term "Yellowstone fires" may be misleading; five of the eight major fires started outside of the park and burned into it. Three of these five were started by humans and were fought from the beginning. For example, the North Fork fire was started by woodcutters near West Yellowstone and eventually grew to about 200,000. A

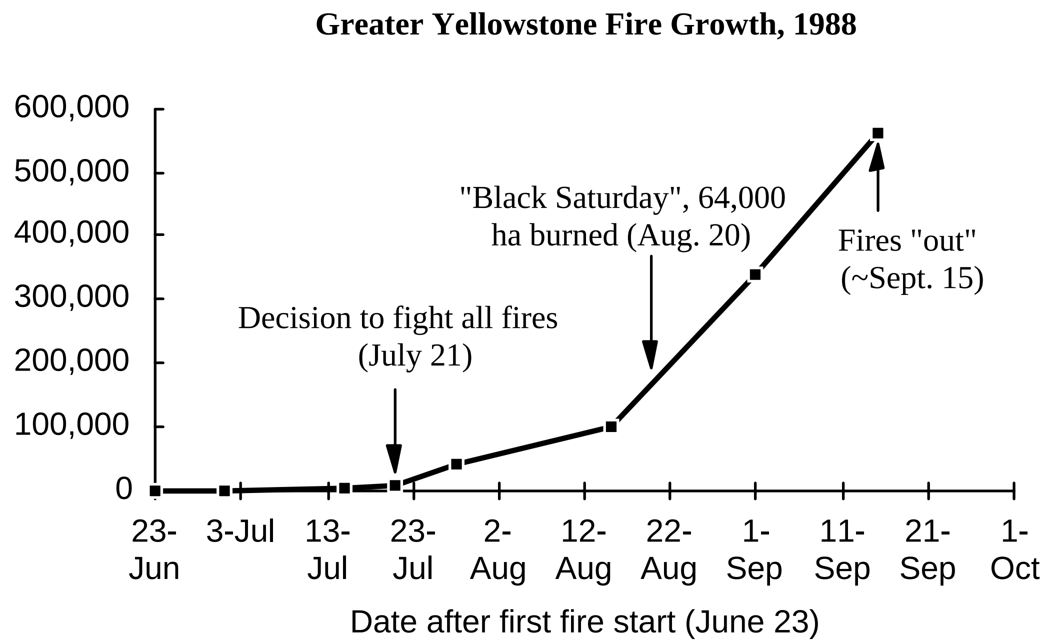

Figure 3. Cumulative curve of burn area in the Greater Yellowstone area during the 1988 fire season (data from Schullery, 1989, and unpublished National Park Service fire information sheets). Fires continued to burn after cold wet weather reduced their intensity on September 15, but relatively little burn area accumulated.

total of 248 fire starts were recorded in the Greater Yellowstone area in 1988 (Schullery, 1989). Some of the fires burned mostly outside of the park, e.g., the lightning-caused Storm Creek fire near the northeastern park boundary. This fire (~7300 ha) most closely threatened the Cooke City area but never crossed the ridge between Pebble Creek and the main Soda Butte valley.

The Clover and Mist fires were started by lightning on July 9 and 11, respectively, in the southeastern corner of the upper Lamar River basin (Carey and Carey, 1989). These two fires joined with several other small natural fires and eventually grew to over 80,000 ha, covering most of the Lamar River drainage above Soda Butte Creek and extending over the divide into the Clarks Fork and Shoshone River basins.

The total cost of fighting the fires was approximately $120,000,000. Although fire-fighting efforts probably had little effect on the total area burned, the protection of structures in Yellowstone and surrounding areas was actually quite successful. A total of 67 structures were destroyed, primarily small buildings and park cabins; the venerable log structure of the Old Faithful Inn was saved despite the passage of the September 7 fire storm over the entire development (Schullery, 1989). Despite the potential hazard to firefighters, only one person was killed by a falling tree in October in the Crandall Creek area.

About 75% of the lodgepole pine-dominated forests of the Lamar River drainage above the Soda Butte confluence were canopy burned in 1988 (Barrett, 1994), and the Hellroaring and Slough Creek drainages were also extensively burned (Schullery, 1989). The high-elevation forests of northeastern Yellowstone are particularly susceptible to extensive burns, because many of the major valleys are oriented NE-SW, parallel to the prevailing wind, and steep slopes allow convection to carry fires upslope. Many steep first- and second-order basins throughout northeast Yellowstone were almost completely covered by intense canopy burns (Minshall et al., 1989). Such basins are the primary source areas for fire-related debris flows and floods (Meyer, 1993a).

The effect of fire suppression on the intensity and areal extent of the 1988 Yellowstone fires was probably small (Romme and Despain, 1989). Suppression efforts had limited impact on backcountry fires before the advent of aircraft support ca. 1945, and the natural fire policy initiated in Yellowstone NP in 1972 allowed fires that did not threaten developed areas with to burn unhindered (Schullery, 1989; Carey and Carey, 1989). Fire suppression was potentially effective over about 30 years, which is only about 10-20% of a typical fire cycle in the high-elevation forests of Yellowstone (Romme and Despain, 1989; Barrett, 1994). The nature of the 1988 fires was probably not strongly influenced by modern management activities, and thus they can provide a reasonable analog for interpretation of major postglacial fires and their geomorphic effects.

Forest fire regimes

Fires, like most natural phenomena, are highly variable in their behavior. Frequency, magnitude, and intensity of fires vary depending on the environment in which they occur and the particular weather conditions during burning. Within the greater Yellowstone area, fires were fairly frequent in the more open lower-elevation forests in the period before fire suppression, with recurrence intervals of about 15-50 years (Houston, 1973; Barrett, 1994). In Yellowstone National Park, such forests are restricted mainly to the lower parts of the Yellowstone River and Lamar River drainages in northern Yellowstone. Lower-elevation fire regimes are characterized by smaller, low-intensity fires. These surface fires burn through understory vegetation and often kill young trees, but leave many mature trees scarred but alive. By removing small trees, such fires help to maintain the relatively open character of these forests.

In contrast, the denser subalpine forests which dominate Yellowstone tend to burn in widespread, intense, stand-replacing canopy fires such as occurred in 1988; less intense fires do occur, but are much more limited in area and ecological effect (Romme, 1982; Romme and Despain, 1989). High-elevation forests with continuous canopies may not experience significant fires for intervals of 150 to 350 years or more, although these estimates are based largely on measurements of one cycle (i.e., the age of the last widespread stand-replacing fires) and models of successional control of flammability (e.g., Romme and Despain, 1989). Even widespread intense fires generally produce a mosaic of burned and unburned patches, but first- to fourth-order drainage basins are often burned completely, as in 1988 (Minshall et al., 1989).

Using dendrochronology, Romme (1982) and Romme and Despain (1989) found a 300-400 yr fire return interval in the lodgepole forests of the rhyolite plateaus of central Yellowstone. These forests become most flammable after 150-300 years following a stand-replacing fire. Barrett (1994) determined a multiple-site average fire interval of about 200 years for stand-replacing fires in the lodgepole pine-dominated forests of the Lamar River drainage above Soda Butte Creek, a significantly shorter interval than the on the less productive Yellowstone Plateau. Only one age class of stands (dating at ca. 1647 AD) predated 1737 AD, thus multiple cycles are not represented, and the question of whether Holocene climate variations produced changes in fire regimes could not be evaluated.

Whitebark pine-dominated stands near timberline in the Lamar area date back to the 1500s and yielded a multiple site average fire interval of about 340 years (Barrett, 1994). These forests are believed to burn only during times of extreme fire weather, such as occurred in 1988 (Despain, 1990; Renkin and Despain, 1992), thus this longer interval may more closely represent the frequency of very large, widespread, and intense fires. Lower-elevation Douglas-fir stands burned with much more frequent surface fires (15-50 yr return intervals). The geomorphic effect of such surface fires is likely to be small, as they do not necessarily kill larger trees, and burn over areas of relatively gentle slope.

Changes in fire activity over longer timescales have been investigated by charcoal counts in lake cores in central Yellowstone. Detailed records from several lakes indicate that relatively large areas burned ca. AD 1700, 1560, and 1440, whereas lesser fire activity occurred ca. AD 1220-1440 and 1700-1987 (Millspaugh and Whitlock, 1995). Analysis of a longer core suggests that in general, fire frequencies in the early Holocene were substantially greater than in the late Holocene (Millspaugh and Whitlock, 1994).

The occurrence and behavior of fire in northeastern Yellowstone is strongly dependent on weather. Drought and wind conditions during the concurrent summer season are of primary importance (Romme and Despain, 1989; Balling et al., 1992a, 1992b). Antecedent conditions, e.g., snowfall over the preceding winter, are significant in the development of drought conditions for a particular fire season, as are larger-scale climatic patterns (e.g., Trenberth et al., 1988).

Because intervals between major stand-replacing fires may be up to several hundred years, centennial- to millennial-scale climate change during the Holocene may have been highly influential in the occurrence of these fires. The high-elevation forests of the greater Yellowstone area tend to burn very little in the majority of years, suggesting that the thresholds of flammability are strongly controlled by fire weather. Climatic change involving increasing warmth and/or decreasing precipitation may greatly increase the probability that the drought threshold for catastrophic fire will be crossed. Conversely, relatively cool and moist climate may delay the occurrence of major fires, perhaps for hundreds of years, and restrict fire activity to small, low-intensity burns with limited geomorphic effect (Meyer et al., 1992, and 1995).

Historical climate-fire relations in the Yellowstone area

Balling et al. (1992a, 1992b) studied the relationship between fire activity in Yellowstone National Park and climate over the period of instrumental records in the park and surrounding areas (Figs. 4 and 5). Fire data used in the analyses consisted of annual area burned within Yellowstone National Park within the period of 1895-1990. These were obtained from historical records (U.S. National Park Service-Yellowstone, reports on file; Taylor, 1969, 1974) and by estimation of burn areas on air photos for the period prior to 1930 (provided by Don Despain, National Park Service-Yellowstone Center for Resources). Inspection of the burn area record shows that 97% of the burn area over the last 95 years occurred in only seven "large-fire" years (1910, 1919, 1931, 1940, 1979, 1981, and 1988) and that 1988 produced 88% of the total area.

Climate data consisted of monthly values of mean temperature, total precipitation, and the Palmer Drought Severity Index (PDSI), a widely-used indicator which combines precipitation and estimated evapotranspiration to estimate drought effects on soil moisture conditions (Palmer, 1965). In order to investigate the sources of climatic variance, principal components analysis was conducted on a data matrix that included temperature and precipitation values for the concurrent summer and the antecedent winter for a given fire season (Balling et al., 1992a). Loadings revealed that component #1 was strongly related to high summer temperature and low summer precipitation, thus is a drought indicator for the concurrent summer. Loadings for component #2 show that it indicates antecedent winter drought. When component scores for each year are compared to the annual burn area times series (which is highly skewed by rare large-fire years), the resulting Spearman rank-order correlation coefficients suggest that over 36% of the variance in annual burn area data can be explained by the above climate variables, and that summer drought is of primary importance.

A discriminant analysis was used to predict the occurrence of large-fire years using the two drought-related components. The discriminant function was able to correctly reclassify six of the seven large-fire years and 67 of 88 small-fire years. Correlation of summer (July-Sept.) PDSI and burn area values over the historical period also shows that about one-third of the burn area variance may be due to seasonal drought (Balling et al., 1992b).

These results indicate a strong control of annual weather on fire activity. Only the 1988 fires, however, were of major ecological and geomorphic significance (cf. Christensen et al., 1989; Romme and Despain, 1989; Meyer et al., 1992). Although the vast majority of the area burned in the last 100 years was burned during the 1988 fire season, climatic trends leading up to 1988 may be important to the occurrence of the severe summer drought. Principal component scores (Balling et al., 1992a) imply that concurrent summer drought has increased over the period, but not at a statistically significant rate. Winter drought did increase significantly, because of both increasing temperature and decreasing precipitation.

Summer PDSI values, however, show a decline of -0.019/yr since 1895 that is significant at the 95% level of confidence, indicating an increasingly drought-prone climate (Fig. 4). This trend culminated in the 1988 summer drought, which produced the lowest recorded PDSI value of about -6; for comparison, -5 is considered extreme drought. The outbreak of very large fires in 1988 may thus relate to a long-term trend of increasing drought (Balling et al., 1992a, 1992b). The extreme nature of the 1988 drought is also illustrated by the summer precipitation time series for the Northeast Entrance of Yellowstone (Fig. 2).

Analysis of an extended array of precipitation and temperature variables showed that the trend of increasing drought in Yellowstone is related primarily to decreasing winter precipitation and secondarily to increasing summer temperature (Balling et al., 1992a, 1992b). Winter precipitation and summer temperature are also significantly and negatively correlated. Summer precipitation, however, has increased slightly in the last ~100 yr in the Yellowstone area; this increase is significant at the 99% level at the two Yellowstone stations with long records (Mammoth and Yellowstone Lake) (Balling et al., 1992b). The drought trend thus appears to be characterized by increasing warmth and increased summer "monsoonal" precipitation, which is replacing a cooler climate characterized by heavier winter precipitation. Climatic change of this nature could have a strong influence not only on the probability of large, geomorphically significant fires, but on the relative magnitude and timing of snowmelt and convective-storm runoff as well, which are primary independent variables in Yellowstone alluvial systems. Snowmelt is prolonged and produces the great majority of the annual runoff, whereas convective-storm runoff is brief, restricted in area, and a small proportion of the total annual runoff in Yellowstone at present (Ewing and Mohrman, 1989; Slack et al. 1993). Convective-storm runoff, however, may produce very high to extreme discharges in steep tributary drainages; these discharges are capable of doing a substantial amount of geomorphic work over a brief period.

The possibility of defining characteristic atmospheric circulation patterns associated with fire activity in the western U.S. has been previously considered. In a study combining tree-ring and historical records of fire and climate, Swetnam and Betancourt (1990) were able to establish a strong relation between annual area burned in National Forests of Arizona and New Mexico and the Southern Oscillation Index (SOI), a measure of the state of the El Nino-Southern Oscillation climate phenomenon in the tropical Pacific. Historically, winter and spring precipitation over much of the southwestern U.S. is significantly and negatively correlated with the SOI (lagged four months), with higher precipitation in the southwest during low-index phases (i.e., El Nino events). An equally strong and significant positive correlation (i.e., low winter precipitation) is seen in parts of the northwestern U.S., including the Yellowstone Drainage climate division and much of western Montana. Also, the Pacific-North America (PNA) index correlates positively and significantly with Yellowstone-area winter precipitation. A low PNA index describes a circulation pattern characterized by an anomalously deep Aleutian and southeastern U.S. lows and an intensified high pressure ridge over western North America; opposite anomalies exist during high phases (Redmond and Koch, 1991).

A set of eleven summer atmospheric circulation types for the western U.S. (1945-1987) was identified by Carleton (1987). These data were updated by R.C. Balling, Jr. and coworkers at Arizona State University, and the frequency of occurrence of each circulation type during the fire season (July 1-September 15) was compared to burn area in Yellowstone National Park for the same period (written communication, 1992). Only one correlation coefficient with circulation type #8 (+0.322) was determined to be significant at the 95% level of confidence. This pattern is characterized by surface high pressure centered over southeastern Texas and an upper level ridge along the eastern front of the Rocky Mountains (Fig. 5). Considering the surface climate effects of the low PNA index pattern discussed above, these findings imply that both winter and summer drought conditions in the Yellowstone region are associated with persistent high-pressure ridging over western North America. Application of characteristic circulation patterns to considerations of Holocene-scale climate change in Yellowstone, however, remains to be accomplished.

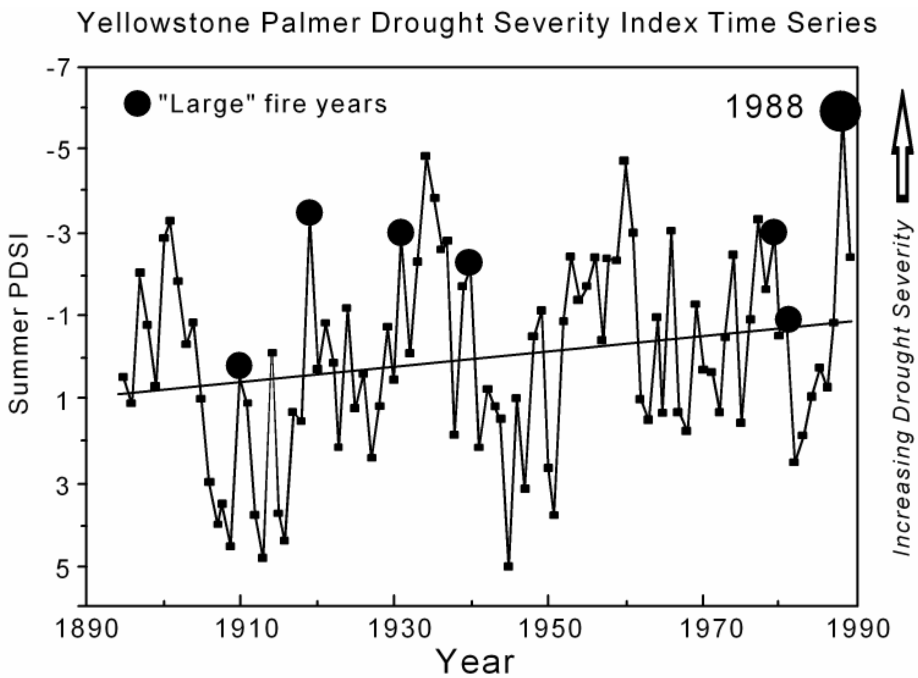

Figure 4. Summer Palmer Drought Severity Index values for the Yellowstone Drainage and Snake Drainage climate divisions, 1895-1989 (modified from Balling et al., 1992b). "Large" fire years are those in which 2500 to 9000 ha burned within Yellowstone National Park; however, in 1988, nearly 400,000 ha were burned within the park.

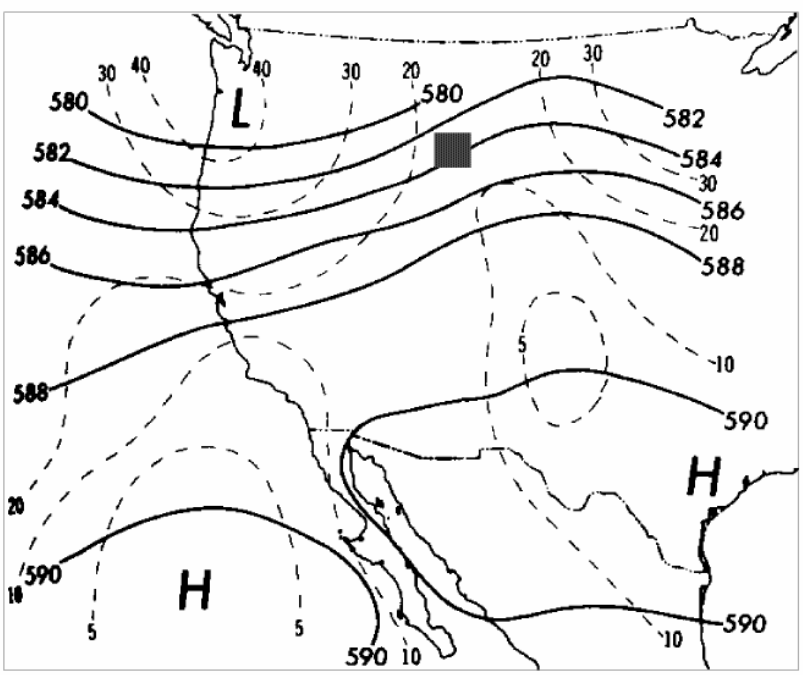

Figure 5. Composite synoptic map of 500 mb heights (solid lines) (gpdm) associated with atmospheric circulation type 8 as defined by Carleton (1987, modified from Fig. 1g), showing location of surface high (H) and low (L) pressure centers. Standard deviations (in m) are dashed. The general greater Yellowstone area is shown by the shaded rectangle.

Road Log

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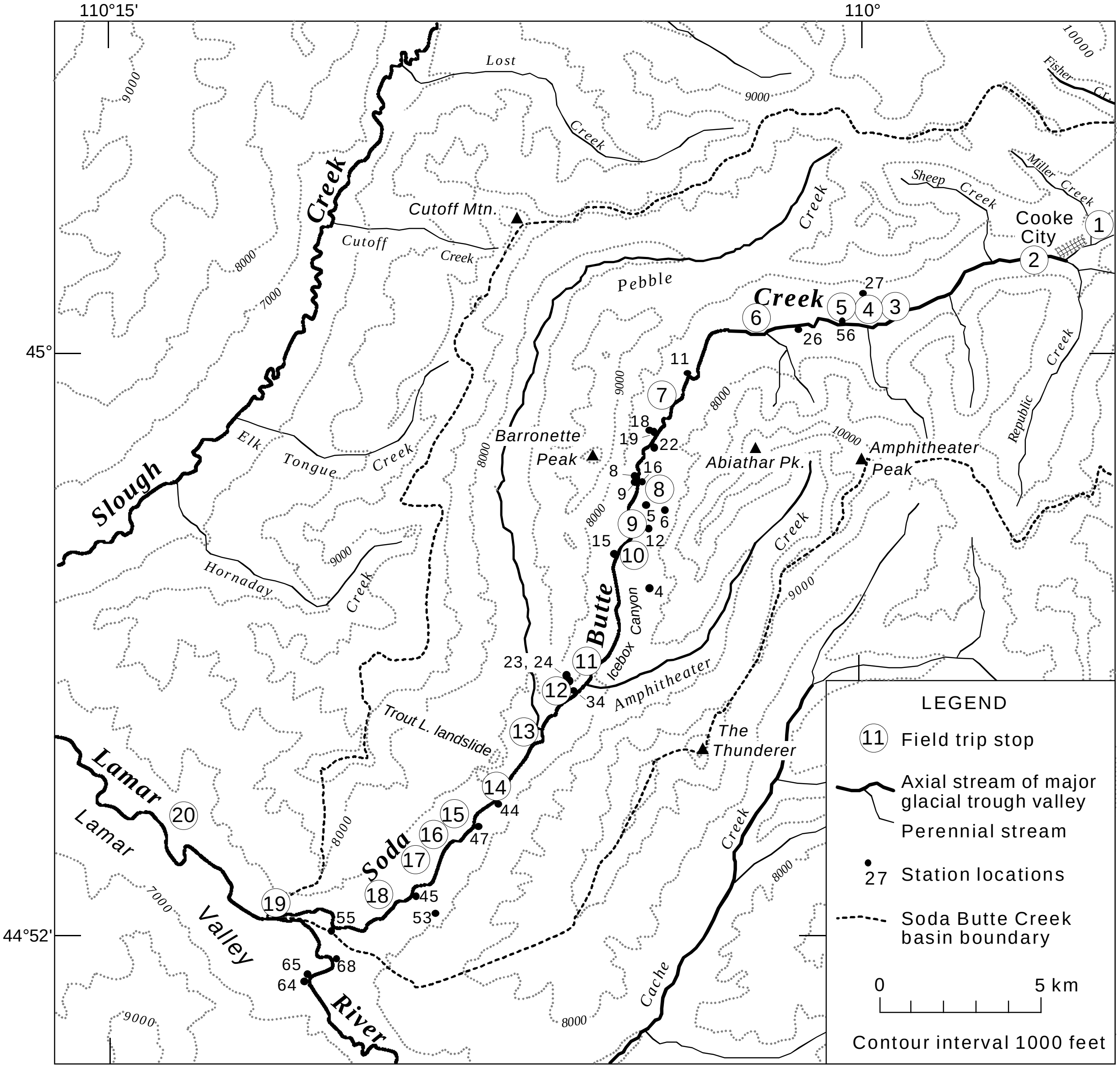
Chief Joseph Campground (Colter Pass) to Lamar Ranger Station, Yellowstone National Park via U.S. Highway 212 (Beartooth Highway and Northeastern Entrance Road)

Mileage from NE Entrance of Yellowstone	
7.2	Chief Joseph Campground on Colter Pass (also called Cooke Pass), US Hwy. 212. Additional parking for those camping elsewhere across Highway 212 at the Clark Fork trailhead.
6.8	Big Bear and Big Moose Resorts. View of Sheep Mountain straight ahead.
6.0	Colter Campground.
5.8	Lulu Pass Road to north. The New World gold mine has been proposed by Crown Butte Mines/Noranda in the Fisher Creek valley about 3 miles up this road, in the headwaters of the Clarks Fork of the Yellowstone River. Probably the most controversial element of the project is the proposed tailings impoundment, which would store 5.5 millions tons of pyrite-rich tails in the bottom of the confined Fisher Creek valley, between Sheep Mountain on the northeast and Henderson Mountain on the southwest. Fisher Creek would be permanently diverted around the impoundment in a low-gradient channel on the southwest side. Debris flows and major snow avalanches have occurred on the steep valley sides, raising questions over the long-term stability of the diversion channel and impoundment. Several alternative impoundment sites are being considered, including a site in the lower relief terrain of knobby Archean gneiss outcrops and moraines about 0.5 miles up the Lulu Pass Road; this site lies within the Soda Butte Creek drainage.
5.2-5.5	Roadcuts in sandy glaciofluvial gravels.
4.8	Soda Butte Campground.
4.6	Daisy Pass Road to north.
4.4	**STOP 1: McLaren tailings.** The McLaren mine was an open pit gold mine located on the south side of Fisher Mountain near Daisy Pass, about 3 miles NNW of Cooke City in the New World mining district. Between 1933 and 1953, ore was trucked to this site just above Cooke City and processed; tailings were placed in an impoundment here along Soda Butte Creek at the confluence of Miller Creek (Fig. 6). Acid drainage from the tailings has been the subject of EPA remediation efforts.



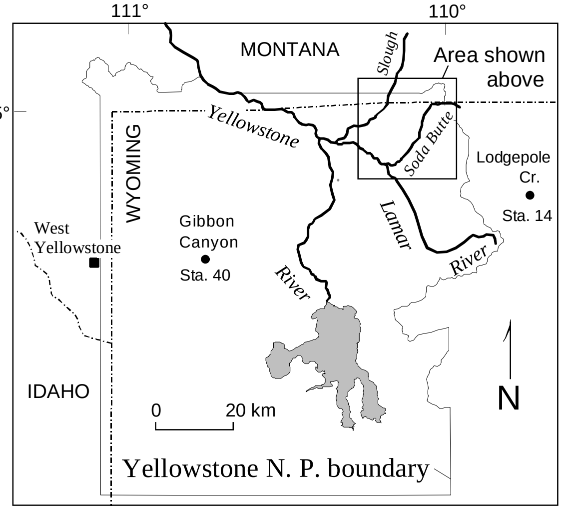


Figure 6. Topographic map of the northeastern Yellowstone area showing field trip stops (circled numbers), selected station locations for stratigraphic sections, and other localities referred to in the road log. Additional stratigraphic section locations are shown in Meyer et al. (this volume). Index map at lower right shows location of field trip area and station locations in the Gibbon Canyon and Lodgepole Creek areas.

Soda Butte Creek Floodplain Tailings Deposits and McLaren Dam-Break Flood

(Grant Meyer and Matthew K. Bingham, Department of Geology, Middlebury College)

Widespread mine tailings sediment contamination along the Soda Butte Creek floodplain has recently been documented (Meyer, 1993b, 1995). Deposits of tailings are typically present as a single, discrete layer of strongly oxidized fine sand to clay-sized material lying at or near the floodplain surface, implying emplacement in a single flood. They range in thickness from 35 cm or more just below Cooke City to a few centimeters near the Lamar River confluence, 30 km downstream from the tailings impoundment.

The tailings-depositing flood was largely unrecorded, as streamflow gaging postdates 1989 on Soda Butte Creek, but long-time Cooke City resident Jack Williams (interviewed by local historian Ralph Glidden in 1992) recalled a failure of the McLaren tailings impoundment during the summer of 1950 or 1951. Williams believed that the dam break was due to a series of heavy rainstorms in the upper Soda Butte basin, and that possibly, failure of small tailings pond on Miller Creek added to the flood flow which breached the dam. He also recalled that the mill operators were seeking to expand the impoundment at that time; this suggests that it was nearly full of tailings and lacking in storage space for flood runoff. National Park Service records mention a major dam break and tailings spill from the McLaren impoundment in June 1950. Although no specific date for the dam failure was given, the report states that the break was being repaired on June 28, 1950.

Reconnaissance sampling suggests that concentrations of copper and lead in the tailings sediment decline exponentially downstream, e.g., from ~1200 ppm Cu near Cooke City to about 300 ppm Cu near the Lamar River confluence (Fig. 7). Concentrations of copper in the tailings sediments substantially exceed the 100 to 125 ppm level considered to be toxic to plants, and lead is near the toxic threshold of 100 to 400 ppm (Kabata-Pendias and Pendias, 1984; see also Marcus et al., this volume).

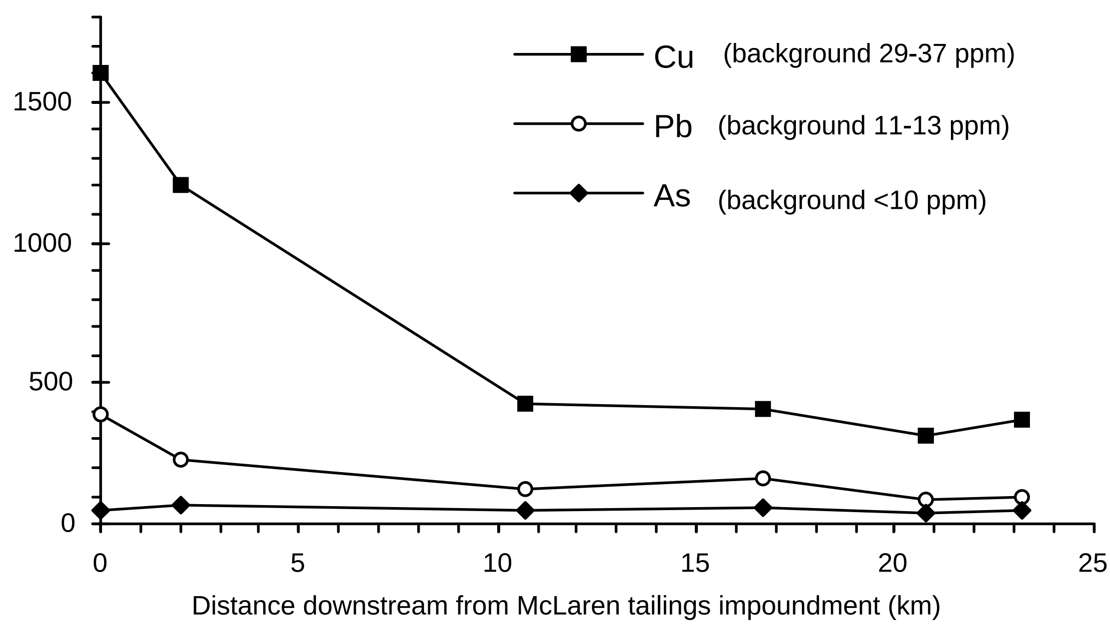


Figure 7. Concentrations of selected elements in Soda Butte Creek floodplain sediments deposited by the 1950 McLaren tailings dam-break flood. Concentrations at 0 km are an average from the McLaren tailings impoundment site. Background values were obtained from pre-mining fluvial overbank sediments sampled from late Holocene terraces. The Lamar River confluence is at ~26 km.

We used slope-area and particle size-velocity relationships to estimate peak discharge during the tailings dam-break flood in Round Prairie, about 20 km below Cooke City at about 3600 ± 700 cfs (~100 ± 20 m^3/s) (see Stop 10). Although this discharge is slightly less than the ~4000 ± 900 cfs estimated for this reach by dam-break models (using dam height and size of breach), it does not include shallow flows outside of the primary flood channel. These peak discharge values substantially exceed the 100-yr flood of 1800 cfs estimated for this reach through USGS multiple-regression equations, which employ regional streamflow data and basin characteristics (Omang et al., 1986). Most regional streamflow records, however, begin after major floods of the late 1800's and early 1900's. On Soda Butte Creek at Round Prairie, estimated discharges for natural floods in 1918 and ca. 1873 are about 2-3 times larger than the dam-break flood.

Although peak discharge during the dam-break flood was relatively high in the upper Soda Butte valley, geomorphic work accomplished by the flood (e.g., bank erosion, channel incision, and gravel bar deposition) was relatively minor, probably because the flood was of short duration (Costa and O'Connor, 1995). Nevertheless, a substantial mass of tailings was deposited on the floodplain during high stages; detailed mapping and volume estimation for these deposits is currently underway. Channels formed during the earlier, more effective floods acted as slackwater areas during the dam-break flood and accumulated thicker tailings deposits. Tailings sediments may affect water quality in Soda Butte Creek through leaching by infiltrating precipitation or shallow groundwater, and through remobilization of thick deposits below Cooke City by bank erosion and overbank flooding.

3.9 Cooke City (General Store in center of town).

3.1 **STOP 2: Soda Butte Creek floodplain tailings deposit.** A short dirt road leads down to Soda Butte Creek about 2 km downstream of the McLaren tailings impoundment, where a thick accumulation of tailings deposited by the 1950 dam-break flood is present on the floodplain surface. The tailings sediment at this site is over 20 cm thick and contains 1200 ppm Cu and 230 ppm Pb. A recent rockslide in Eocene volcanics is visible on Republic Mountain to the south.

2.8-3.1 Numerous small slumps in roadcuts on north side, where groundwater discharges from till.

2.6 **Sheep Creek alluvial fan.** Bouldery lobes and levees in the fan apex area above the road give evidence for debris-flow activity.

2.4 Till with granitic erratics on north side of road.

2.2-2.3 Road crosses an alluvial fan with an active channel along the west margin. A berm has been constructed for protection of a cabin near the channel. The berm is built of relatively fine sediment, however, and could be breached by a large flood or debris-flow event. This channel has covered the road with debris a number of times in recent years.

1.4-2.1 **Mineral Mountain (a.k.a. Silver Mountain) alluvial fan.** Note the high relief of this large postglacial alluvial fan as the road crosses over it.

1.6 Active channel of Mineral (Silver) Mountain fan. Highly sediment-charged floods have caused problems for adjacent development.

1.0 **STOP 3: Silver Gate,** elevation ~7390 ft. The prominent high peak to the SSW is Amphitheater Peak (11,042 ft). A small moraine fronting the perennial snowfield at the head of the northeast cirque (elevation ~9900 ft) is little vegetated, very sharp-crested, and has a distal slope of about 38˚, suggesting an age of no more than several hundred years (designated as "Gannett Peak" age by Pierce, 1974a). The northwest end of this moraine has been buried by what appears to be a rockfall avalanche deposit or rock glacier. This and a few other sharp-crested moraines that lie in well-shaded cirque heads in the Soda Butte Creek drainage were probably formed by Little Ice Age advances. Rounded, well-vegetated moraines of probable latest Pinedale age occur a only few hundred feet below this terminal position and extend down to about 8800 ft (Pierce, 1974a; personal communication, 1989). To the north, numerous small channels with levees and small debris flow lobes are seen on the talus slope on Mineral (Silver) Mountain. The Eocene volcanics in this area are massive autobreccias that are somewhat more conducive to talus formation than the fines-rich, friable "alluvial facies" volcaniclastics further downvalley, west of the Heart Mountain breakaway (Prostka et al., 1975b; see Stop 6).

0.5 **STOP 4: Silver Creek alluvial fan.** The obvious cleared area which crosses the road here is a firebreak constructed in early September 1988 using heavy equipment in an effort to protect Silver Gate and Cooke City from the Storm Creek fire, which was advancing from the Pebble Creek drainage to the west. The firebreak extends from steep cliffs on lower Amphitheater Peak to the south, to near timberline on Meridian Peak to the north. The Storm Creek fire did not cross the ridge into the Soda Butte Creek drainage. The backfire set to the west of the firebreak, however, was driven by high west winds (the prevailing wind direction in the valley) and jumped the firebreak on September 4. Fortunately for local residents and businesses, an unusual south wind on the morning of September 7 allowed other backfires set above the developed area to burn up the north valley wall away from Silver Gate and Cooke City, and with effort concentrated on protecting structures, only minor property damage ensued. We will hike up the firebreak to Station 27 at the apex of the Silver Creek alluvial fan (Fig. 6). This fan is constricted in its proximal area between Pinedale lateral moraines.

Fire-related Deposition on the Silver Creek Alluvial Fan (Station 27)

The Station 27 exposure on the east wall of the deeply incised fanhead channel displays two examples of stratigraphic units used to infer fire-related sedimentation: (1) A muddy, poorly-sorted, charcoal-rich unit at about 4 m depth was interpreted as a gravel-poor *fire-related debris flow* deposit. These facies are common in fan sediments in northeastern Yellowstone (see Meyer et al., 1995, Fig. 2). Matrix tends to separate from the less mobile bouldery fronts during debris-flow movement and deposition, producing extensive gravel-poor facies (Fig. 8). The voluminous matrix material in fire-related debris flows probably results from extensive sheetwash and rilling of fines-rich burned soil surfaces. Charcoal from this unit dated to 2190 ± 90 yr BP. (2) A buried burned soil surface at about 1.9 m depth, dated at 1870 ± 90 yr BP. This thin, discrete, charcoal-rich layer contains abundant charred conifer needles and other elements of the forest duff layer, and is little bioturbated. The burn surface is overlain by a thin, relatively well-sorted sand, which was probably deposited shortly after fire (i.e., *probable fire-related sediment*). The overlying bouldery debris-flow unit is not obviously charcoal-rich and was not interpreted as fire-related.

Alluvial Fan Sedimentology in Northeastern Yellowstone

Alluvial fan deposits were classified in three major groups based on inferred depositional process: *debris flow*, *hyperconcentrated flow,* and *streamflow* facies, in order of decreasing sediment concentration in the sediment-water flow. No strict quantitative boundaries based on sediment concentration can be placed on these processes, because flow properties vary with sediment characteristics (for example, the percentage and type of clay; Pierson and Costa, 1987). Inertial granular flows of low to very low water content (i.e., debris and rockfall avalanches) also run out from steep basins onto many alluvial fans (Blair and McPherson, 1994), including those in the field trip area. Most of rockfall and debris avalanche deposits in northeastern Yellowstone, however, are very large relative to the valley-side alluvial fans, thus are major landforms in their own right (Fig. 1).

Debris flow is characterized by high sediment concentrations, substantial yield strength, and flow of water and sediment as a single phase (Pierson and Costa, 1987). Sediment size typically includes a wide range of material, from clay and silt to gravel, often including large boulders (Costa, 1988). Very poor sorting aids in flow, and the presence of clay adds cohesion to the matrix fluid.

Although the majority of debris flows probably initiate as *en masse* failures (e.g., Costa, 1988), fire-related debris flows in northeastern Yellowstone were produced by progressive sediment bulking of surface runoff with fine slope sediment, and with coarser material from channel incision (Meyer et al., 1992, and 1995; cf. Scott, 1988). The matrix fluid of fire-related debris flows in the Slough Creek drainage had an estimated sediment concentration of 64-69% by weight (Meyer, 1993a). Deposits are characterized by very poor sorting, random orientation of large clasts, and a finer, generally muddy matrix. Gravel-poor debris-flow facies are formed by runout of more fluid matrix during movement and deposition of the flow, similar to the precursory surges described by Pierson (1986). These "mudflow" facies comprised half of the sediment volume deposited in some fire-related debris-flow events (Meyer, 1993a) (Fig. 8). Textures of debris-flow deposits in northeastern Yellowstone vary depending on basin lithologic and geomorphic characteristics. Although sorting is very poor in debris-flow units in Soda Butte Creek alluvial fans, they are somewhat finer than those observed in Slough Creek after 1988 (Figs. 10, 11). This may be due to differences in available sediment, or perhaps because runoff from exposed bedrock in the Soda Butte basins tends to dilute the flow and allow coarser particles to settle out of the low-strength slurry. Debris flows unrelated to fire also occur in northeastern Yellowstone, usually in basins with the most highly erodible and clay-rich Eocene volcaniclastic rocks, or locally where glacial sediments or Cambrian shales are subject to saturation and *en masse* failure. Colluvium is rarely thick enough to fail *en masse* and produce debris flows (cf. Reneau and Dietrich, 1987).

Hyperconcentrated flow is transitional between debris flow and fully turbulent, dilute streamflow. Hyperconcentrated flows have a small but significant yield strength (Pierson and Costa, 1987). Deposition occurs by particles dropping out of the flow in a rapid grain-by-grain fashion, as opposed to the "freezing" of a single-phase sediment-water mixture. Sedimentological characteristics are transitional between debris flow and streamflow deposits (Smith, 1986; Wells and Harvey, 1987; Scott, 1988; Smith and Lowe, 1991). The primary textural difference is a greater degree of sorting in hyperconcentrated-flow deposits (Figs. 10, 11). Although fabrics of coarse-grained hyperconcentrated-flow deposits are not well understood, crude horizontal stratification and grading patterns are typically noted; flat clasts often show a surface-parallel orientation (Smith, 1986).

Streamflow has a sediment concentration which is too low to have significant effect on flow properties, and includes familiar processes of fluvial deposition from traction and turbulent suspension. In the alluvial fan setting of this study, however, streamflow deposits are of two general types (Bull, 1977; Blair and McPherson, 1994): (1) channel deposits, which occur within and at the mouths of incised fan channels, and (2) sheetflood deposits, which are produced by shallow unconfined flow (depth usually 0.1-0.5 m). Figure 9 shows the mapped distribution of facies in a streamflow-dominated flood event from a burned basin in upper Slough Creek. Channel deposits are more typical of proximal fans and include boulder and cobble bars and lobes, often with well-developed imbrication. Sheetflood gravels and sands have well-developed surface-parallel stratification, sometimes with upward-fining trends within individual beds; imbrication is variable. Particle size in a vertical sequence varies within a restricted range, but deposits of single events show marked fining in the downfan direction because of loss of competence in the strongly diverging flow (Wells and Harvey, 1987; Blair, 1987) (Fig. 9). The common textural characteristic of streamflow deposits on alluvial fans is a relatively high degree of sorting (Fig. 11).

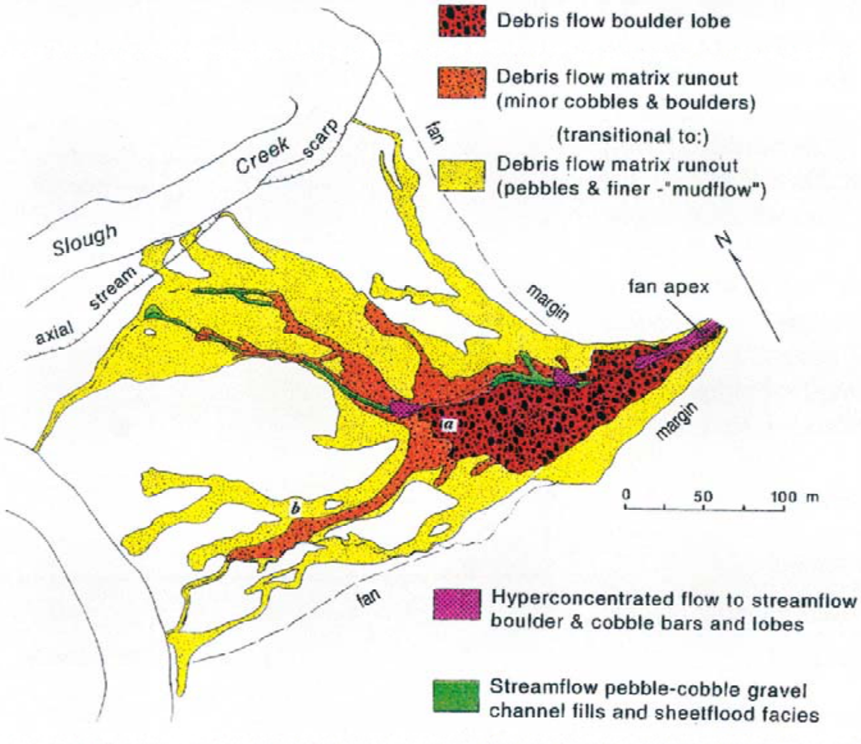


Figure 8. Facies map of the "12 km" alluvial fan, middle Slough Creek, showing deposits of a July 9, 1989 fire-related event dominated by debris-flow processes. Boundaries between debris-flow facies are locally gradational. Small streamflow channels are shown by dot-dash lines. Letters *a* and *b* show locations of photos in Figs. 2a and b, Meyer et al. (this volume).

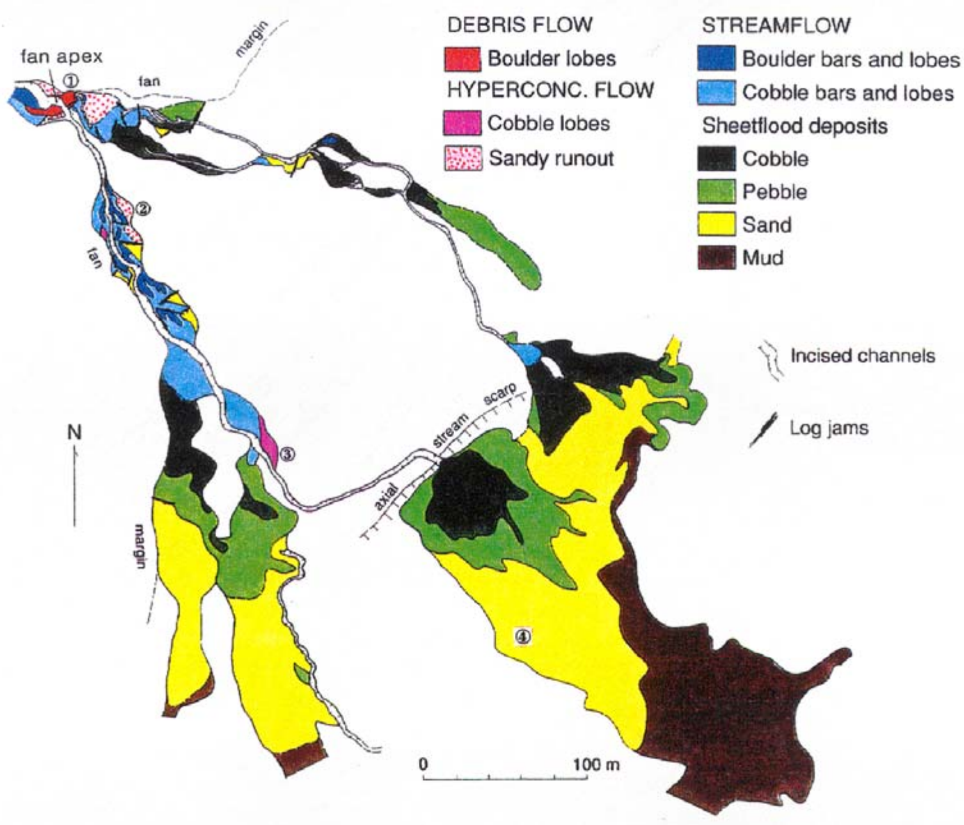


Figure 9. Facies map of the "Frenchy's Meadow" alluvial fan in upper Slough Creek, showing deposits of a 1991 fire-related event dominated by streamflow deposition. Boundaries between sheetflood textural facies are gradational. Although depositional processes were very different, the basin and fan characteristics (e.g., morphometry, burn area, and burn intensity) were similar to those of the "12 km" event; only the year and season of the event (late April or early May) differed greatly.

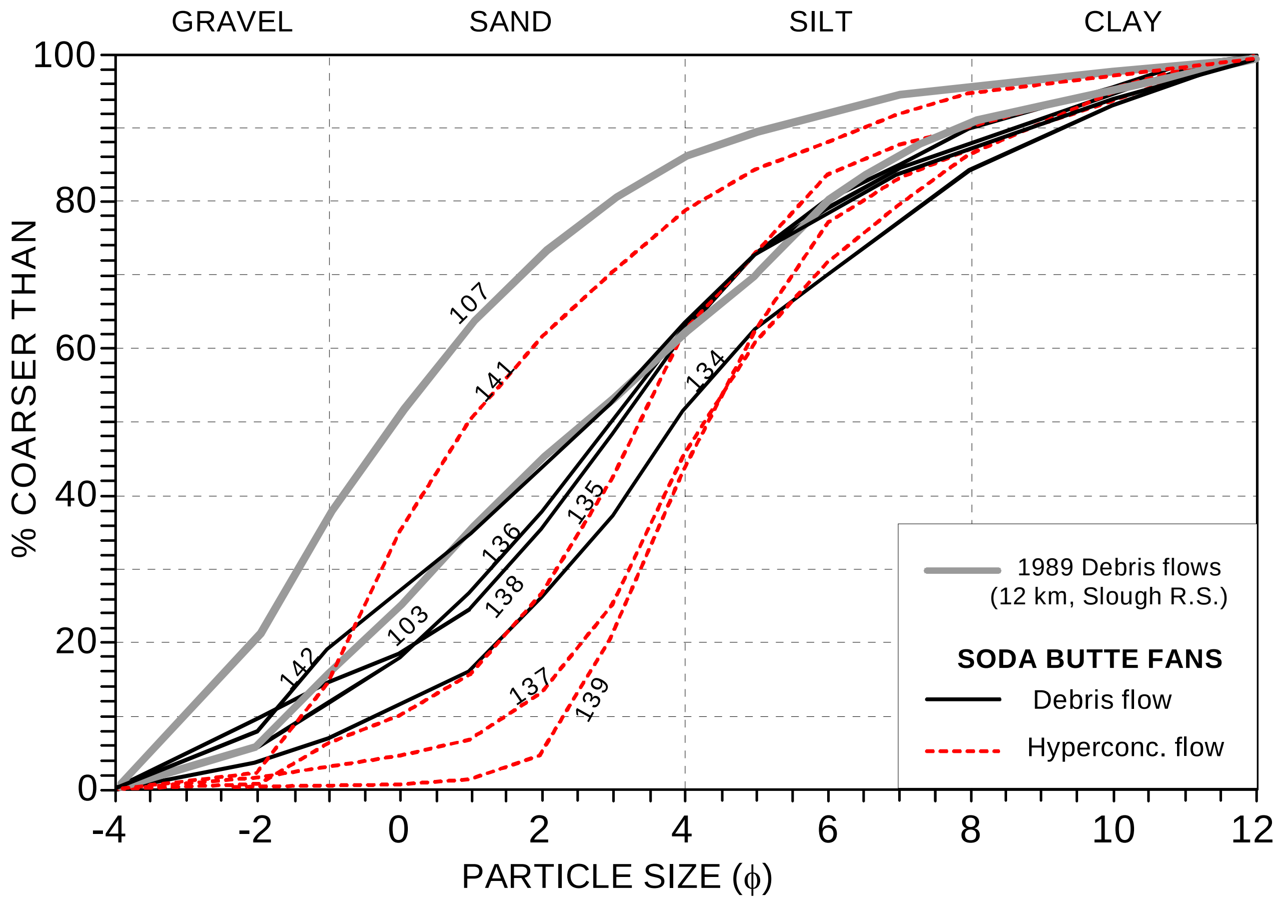


Figure 10. Cumulative curves of particle size distribution in debris- and hyperconcentrated-flow deposits in Holocene alluvial-fan stratigraphy, compared to 1989 post-fire debris flows in northeastern Yellowstone; numbers refer to samples in Appendix 2, Meyer (1993a).

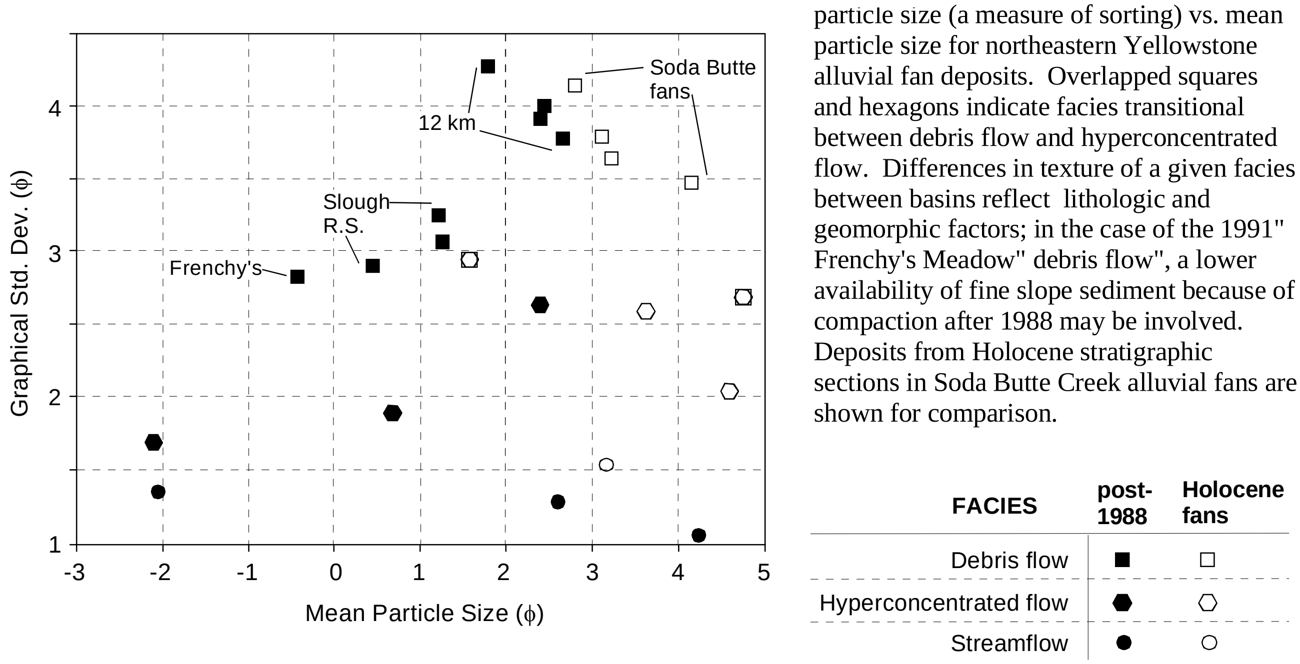


Figure 11. Graphical standard deviation of particle size (a measure of sorting) vs. mean particle size for northeastern Yellowstone alluvial fan deposits. Overlapped squares and hexagons indicate facies transitional between debris flow and hyperconcentrated flow. Differences in texture of a given facies between basins reflect lithologic and geomorphic factors; in the case of the 1991" Frenchy's Meadow" debris flow", a lower availability of fine slope sediment because of compaction after 1988 may be involved. Deposits from Holocene stratigraphic sections in Soda Butte Creek alluvial fans are shown for comparison.

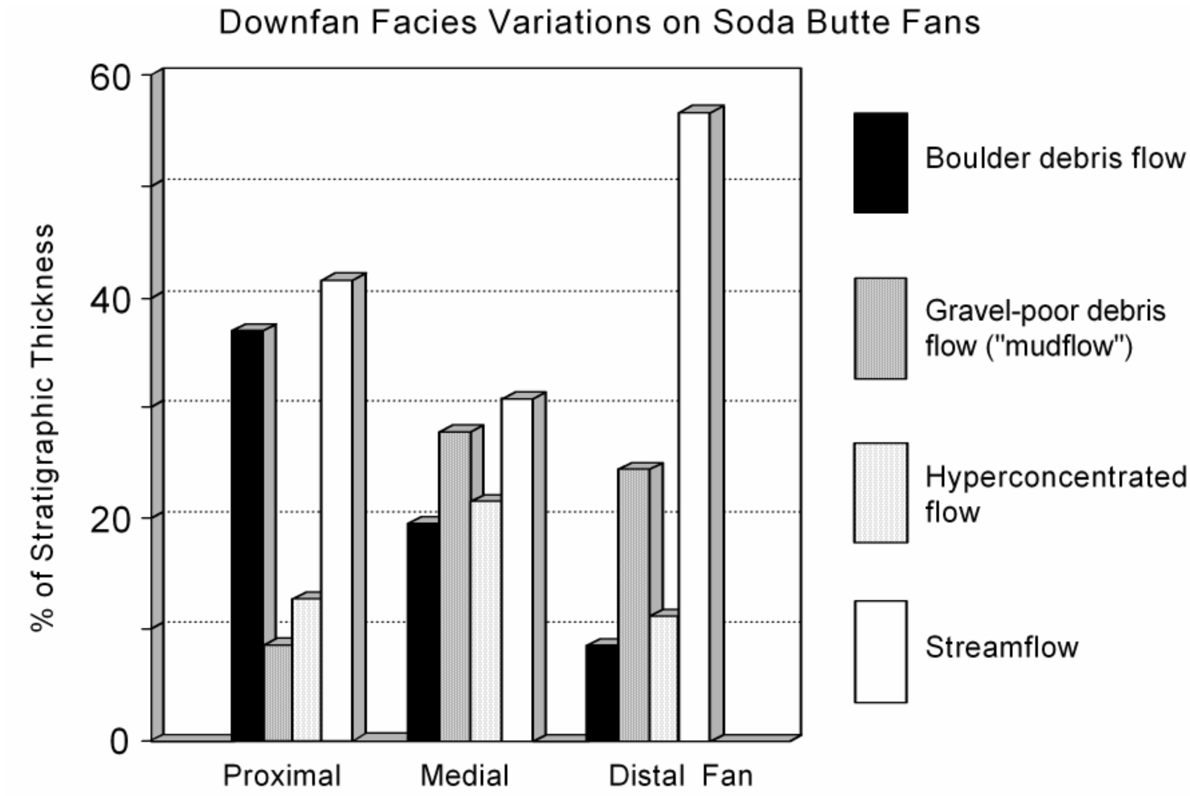


Figure 12. Bar graph showing relative facies abundance in proximal, medial, and distal stratigraphic sections in Soda Butte Creek alluvial fans. Fan positions are defined as: proximal = 0-33%, medial =33-66%, and distal = 66-100% of the radial distance from fan apex to fan toe.

In northeastern Yellowstone fans overall, bouldery debris-flow facies are most common on upper fans, but are replaced by gravel-poor "mudflow" facies on medial to distal fans, reflecting the relative mobility of the flows (Fig. 12). Streamflow facies are most common on distal fans, but are an important stratigraphic component in all fan locations; channelized flows and sheetfloods may occur on all parts of the fan, and dilute flows may rework older deposits of other facies. Hyperconcentrated-flow facies are somewhat more common on medial fans, perhaps because may of these deposits are produced by flood flows causing fanhead-channel incision, sediment bulking of the flow, and resulting deposition of a midfan intersection point lobe.

0.0 **STOP 5: NE Entrance of Yellowstone NP.** The Northeast Entrance Station is constructed on the distal part of an alluvial fan. An excellent exposure of the distal fan is found at Station 56, a Soda Butte Creek cutbank directly below the entrance station.

Station 56 Distal Fan Exposure

This section at the toe of the Northeast Entrance fan (Fig. 6) exposes probable fluvial gravel of Soda Butte Creek at its base. In ascending order, overlying alluvial fan sediments include (1) an 85-100 cm-thick debris flow unit and (2) 35-60 cm of streamflow-facies gravel, capped by a relatively well-developed silt-rich buried soil, and (3) ~50 cm of streamflow-facies fan gravels.

Buried soils are relatively rare in NE Yellowstone alluvial fans; most, like this one, consist primarily of a silt loam A horizon (loess and sheetwash fines?) of about 10YR4/2 color. A weak, 10-30 cm-thick Bk horizon is present below the A in this buried soil, and consists of minor clast-bottom coats and filamentous $CaCO_3$; some of the $CaCO_3$ probably derives from laterally moving water evaporating on the cutbank face. The A horizon contains one or locally two moderately-preserved burn surfaces; charcoal from the upper burn surface at the top of the buried soil yielded an age of 4275 ± 75 yr BP, which was used to infer probable fire-related sedimentation of the overlying streamflow-facies fan unit. The surface soil is also a typical silt loam A over C profile; a second, buried A with top at ~45 cm depth is locally discernible within the fines capping the section. Weak carbonate horizons are present in soils as young as ~1 ka in the Soda Butte Creek drainage, where Holocene sediments are rich in limestone clasts. Fluvial deposits of the Lamar River above the Soda Butte confluence, however, have very few carbonate clasts, and even soils on late Pinedale terrace surfaces have no significant carbonate accumulation (see Stop 18).

Station 56 is one of several dated distal fan localities in Soda Butte Creek and northeastern Yellowstone which provide evidence for a major episode of fan progradation at about 4600-4000 yr BP (see Meyer et al., 1995, and Stop 8). A relatively well-developed buried soil with age bracketed between about 5550 and 3950 yr BP at Station 19 in middle Soda Butte Creek (Fig. 6) also supports interpretation of a period of stability on distal fans prior to about 4600 yr BP.

0.4 Landslide debris in roadcut. This large rockfall avalanche is from the scarp in lower Paleozoic rocks on the north valley wall.

0.45 View to the south across Soda Butte Creek to Station 26, a cutbank in the fan of the drainage including the north cirque of Abiathar Peak (Fig. 6). Probable and possible fire-related sediments in this distal fan section are dated at 3530 ± 50 and 2910 ± 80 yr BP, respectively. A bouldery, limestone-rich diamicton with hummocky morphology just downstream on the south side of Soda Butte Creek suggests a minor landslide-damming event caused by the large landslide from the north valley wall along this valley reach (see preceding and following log entries). Well-stratified fine sediments within the fan section may also have been deposited in a short-lived landslide-dammed lake.

0.5-0.9 Roadcuts in landslide debris from north valley wall and till, or till involved in landslide?

1.0 **STOP 6: Warm Creek picnic area.** The spectacular north face of Abiathar Peak (10,928 ft) is visible to the south, along with the arête connecting to Amphitheater Peak to the east. Latest Pinedale(?) moraines are present at the lower edge of cirques below this ridge (Pierce, 1974a). Large landslide scarps in Paleozoic sedimentary rocks form colorful cliffs on either of the valley in this area (see discussion of the rockfall avalanche from the south side of the valley below).

Heart Mountain Detachment

A minor digression on a world-renowned pre-Pleistocene geologic feature: the steeply west-dipping breakaway fault of the Eocene Heart Mountain detachment is clearly visible in the eastern ridge face, intersecting the ridge crest just to the right (west) of a two-pronged minor peak. The Heart Mountain detachment transported upper-plate rocks 50 km or more southeast into the Bighorn Basin. According to current thought on this controversial structure, the 3400 km^2 Heart Mountain detachment formed either by tectonic denudation (i.e., by catastrophic sliding of blocks on a 2° southeast-dipping surface within the lowermost Ordovician Bighorn Dolomite), with later deposition of volcanic strata against the breakaway surface (e.g., Pierce, 1987); or, by gravity spreading of a continuous extensional allochthon, with downfaulting of volcanics along the breakaway (e.g., Hauge, 1993).

Abiathar North Fan

The large alluvial fan across Soda Butte Creek from the Warm Creek picnic area receives drainage from the north cirque of Abiathar Peak and the cirque to the east below the Abiathar-Amphitheater ridge. Fire-related debris-flow units exposed in the wall of the fanhead trench were dated at 2125 ± 55 and 905 ± 50 yr BP. Just downstream, these units lap onto thick debris-flow unit is exposed which bears no visible charcoal. A possible source for this flow is the toe of the latest Pinedale moraine at the lip of the Abiathar north cirque, which is perched above a cliff of Ordovician Bighorn Dolomite and has slumped into the stream channel below.

At the mouth of the fanhead trench, a broad swath of fresh, unvegetated debris-flow deposits is present. These bouldery deposits grade to finer streamflow facies on the medial and distal fan. Lodgepole pines have recolonized the latter deposits, producing a an apparent even-age stand of younger trees down the lower fan. Coring of this stand reveals that the oldest trees date to about 1947; with a standard -10 yr correction that incorporates lag time for germination and first growth years missing in cores, these data indicate a major debris-flow and flood event about 1937 (see Stop 11 and Fig. 16). Severe thunderstorms caused flooding in the Yellowstone River valley from near Columbus to Billings in the summer of 1937 (Billings Gazette, 1994). The years around 1937 were relatively warm and dry overall, but as in recent warm periods, summer thunderstorm activity may be substantially increased in some years. For example, for the generally warm and dry years of 1983-1987, July and August precipitation at the Northeast Entrance was 43% greater than the 1938-1992 average, whereas precipitation for the remaining months was 13% less than the 1938-1992 average (Fig. 2).

1.1-1.4 Road crosses a complex of fan surfaces.

1.6 Roadcut in alluvial fan or fan-like kame deposits perched a few tens of meters above the level of Soda Butte Creek. The turnout on the southeast lies just above a high, arcuate slump scarp (see following log entry).

1.6-2.8 "Big Bend" of Soda Butte Creek. The major rockfall avalanche from the headscarp in Paleozoic rocks on the south side of valley extends to the southeast bank of Soda Butte Creek along this entire reach.

Rockfall Avalanche From Lower Abiathar Peak and Landslide-Dammed Lake

The lower Paleozoic section is relatively high on the valley wall in this area, which places the notoriously unstable Cambrian Park Shale at the base of the steep glacial trough sidewall, making massive failures more likely. Landslide debris from the fresh-appearing scarp on the south side of the valley forced Soda Butte Creek against fans extending from the north side, causing major erosion and slumping of the fan toes, especially at the apex of the bend in the Soda Butte valley. A high slump scarp is present directly beneath the road turnout at mile 1.6. Laminated silty clays exposed in the west bank of Soda Butte Creek about 500 m downvalley of the road turnout are probably evidence of a landslide-dammed lake. The dam was formed where the downvalley margin of the rockfall avalanche butted against fan and/or kame deposits on the northwest side of the valley. The lake sediments contain abundant organic debris, including wood preserved by anoxic conditions (also indicated by gley colors). A sample from the outer portion of a small log in the central part of a 1.5 m-high exposure yielded a ^{14}C age of 500 ± 70 yr BP (Beta-83656), corresponding to a calibrated age of AD 1429 and 2 σ range of AD 1304-1618 (Stuiver and Reimer, 1993). There appears to be at least 2 m of silty clay above the well-exposed section in the cutbank. If the dated log and its enclosing sediments were indeed deposited in a landslide-dammed lake, the rockfall avalanche dates from the early Little Ice Age (e.g., Grove, 1987; Jones and Bradley, 1992; Luckman, 1993). Greater effective moisture and frost action in this cool period were possibly involved in the failure. Fluvial terraces lying more than 4 meters above the narrow modern floodplain are locally present in the downstream area of the landslide, but are absent in other parts of the middle and upper Soda Butte valley. These features were probably formed during breaching and incision of the landslide dam (cf. Turner and Locke, 1990).

1.8 View of Barronette Peak (10,442 ft) straight ahead.

"Yellowstone Jack" Baronett (*Ralph Glidden, Cooke City Store*)

Barronette Peak is named for Collins Jack Baronett, and has the dubious distinction of being the only place name in Yellowstone that is officially approved in a misspelled form (Whittlesey, 1988).

Born in Glencoe, Scotland in 1827, Jack Baronett deserted ship in China in 1850 for the gold fields of California. Between that time and his arrival in the Montana Territory in 1864, he prospected in Australia and Africa, sailed to the Arctic as second mate on a whaling ship, served with the Confederacy in the Civil War, and fought for the French under Maximilian in Mexico. He worked for many years as a scout in Yellowstone, where despite his background he was known as a gentleman and a very competent, reliable man. He built the first bridge across the Yellowstone River in 1871 just above the Lamar River confluence, where he collected tolls.

Baronett is perhaps best remembered as the man who finally found Truman Everts, a member of the 1870 Washburn expedition who had become lost near the south end of Yellowstone Lake. With the help of his dog, Yellowstone Jack located Everts in the area of "The Cut" between Tower Falls and Mammoth. He at first mistook Everts (who was crawling up a slope in a severely emaciated, fire-blackened, and incoherent state) for a bear: "...My dog began to growl...I saw a black object on the ground. Yes, sure enough there was Bruin. My first impulse was to shoot from where I stood...Then it suddenly occurred to me that it was the object of my search" (Haines, 1977).

Everts had lived for some time by eating the fibrous roots of the large thistle common to the meadows of northern Yellowstone and was suffering from severe intestinal congestion. At a cabin on Turkey Pen Creek, Baronett cared for Everts "with all the care, sympathy, and solicitude of a brother", but for several days it seemed that the starving man would not recover. An old hunter who had stopped by rendered a pint of oil from a fat bear and administered it to the patient, providing him at once with essential nourishment and a remedy for his blockage. Everts survived to write and lecture about his ordeal.

2.3 Active fan channel.

2.7 Upper bridge over Soda Butte Creek. The high cutbank visible on the north side of Soda Butte Creek upstream of the bridge is in an alluvial fan toe. A ^{14}C age of 1725 ± 80 yr BP was obtained on charcoal at ~120 cm below the fan surface in a possible fire-related unit; bioturbation may have mixed ages of charcoal in this unit.

2.7-2.8 Roadcut in debris of another rockfall avalanche from Paleozoic rocks on the lower part of the Abiathar Peak massif that is smaller and probably older than the rockfall avalanche just upvalley. The headscarp area for this landslide is forested, and the deposit has substantial A horizon development. Larger clasts are mostly Cambrian (and Ordovician?) carbonate rocks. Debris from this landslide is also found on the opposite (W) side of Soda Butte Creek in this area, indicating that a low landslide dam probably existed here briefly as well.

3.1 Active channel of small steep fan.

3.6 **STOP 7: Barronette Meadow.** The streamlined form of this hill and granitic gneiss erratics with tops even with the ground surface indicate that it is probably lodgement till. This clearing provides a good view of the very high relief (up to ~3500 feet) and high drainage density of the walls of the Soda Butte trough valley between Abiathar and Amphitheater Peaks. From the top of the hill, the deeply entrenched distal channel of the Station 18-19 fan (Fig. 6) can be seen across Soda Butte Creek. The Soda Butte Creek floodplain is constricted between alluvial fan toes in the middle reach of the valley.

Morphometric Analysis and Flood Potential of Drainage Basins in Northeastern Yellowstone

(Peter M. O'Hara and Grant Meyer, Department of Geology, Middlebury College)

A recent controversy has revolved around the sources of suspended sediment and turbidity in the Yellowstone River above Livingston, Montana. The Lamar River system is recognized as a major contributor of fine sediment. Turbidity in the Lamar River has been ascribed to overgrazing by ungulates in the popular literature (e.g., Chase, 1987), or alternately, to the presence of highly erodible Eocene volcaniclastic rocks and glacial lake sediments (Ewing and Mohrman, 1989). Glacial lake sediments along the upper Lamar River contribute suspended sediment because of bank erosion and slumping during high snowmelt runoff discharges, but become less important after peak snowmelt runoff. Turbidity generates the most concern during the period after peak snowmelt runoff because of impacts to the sport-fishing industry. Observation of numerous turbidity events occurring after the snowmelt peak indicates that most are caused by thunderstorm-generated flash floods in tributary basins with steep exposures of Eocene volcaniclastic rocks (excepting those originating in burned basins after 1988). Significant sources of suspended sediment in the post-snowmelt period have not been identified in lower-elevation grassland and riparian areas, i.e., the ungulate winter range most subject to grazing and browsing pressure. A major source of suspended sediment in flash-flood events is incision of deep channels in the alluvial fans of these small steep basins. Although Soda Butte Creek and the upper Lamar River are often observed to be highly turbid after thunderstorms, Slough Creek is much less commonly turbid, despite a high percentage of poorly indurated volcaniclastic bedrock (Fig. 13).

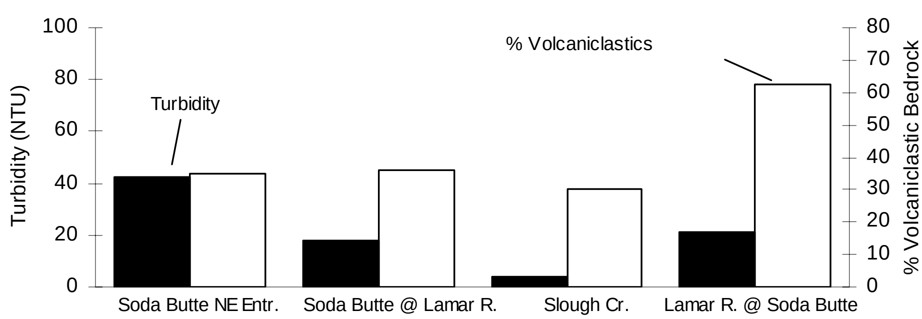


Figure 13. Average turbidity for northeastern Yellowstone streams during the snowmelt and summer seasons, 1985-1986, and percent basin area composed of Eocene volcaniclastic rocks (data from Ewing and Mohrman, 1989). Note the much lower turbidity in Slough Creek despite a similar percentage of volcaniclastic rocks.

To examine the effect of drainage basin morphology on fan channel incision, morphometric parameters for 181 tributary basins were determined, including most basins in the Soda Butte Creek drainage (n=125). Slough Creek basins as far upstream as Bull Creek were studied (n=39), which excluded some headwaters tributaries in erosion-resistant Archean gneisses (i.e., those unlikely to be an important source of suspended sediments). Seventeen Lamar River tributary basins in the Lamar Valley area were also included in the analysis. Channels were classified as (1) *incised* where recent erosion was confirmed by field checking, (2) *possibly incised* where incision was apparent on air photos but not confirmed in the field, or (3) *unincised* where no evidence of recent incision was noted. In the Soda Butte drainage, 27 fans had incised channels, whereas Slough Creek and Lamar Valley fans had no recently incised channels prior to the 1988 fires and subsequent debris flow and flood events. Drainage networks were constructed on USGS 1:24,000-scale topographic maps, and the morphometric parameters of basin area, drainage density, drainage frequency, relief ratio (total basin relief divided by basin length, measured parallel to the longest stream) and ruggedness number (drainage density times total basin relief) were measured. Basin areas ranged over 3 orders of magnitude, from about 0.04 to 40 km^2. Mean values of relief ratio, drainage density, and drainage frequency are all significantly higher in Soda Butte Creek basins than in Slough Creek basins ($\alpha = 0.01$).

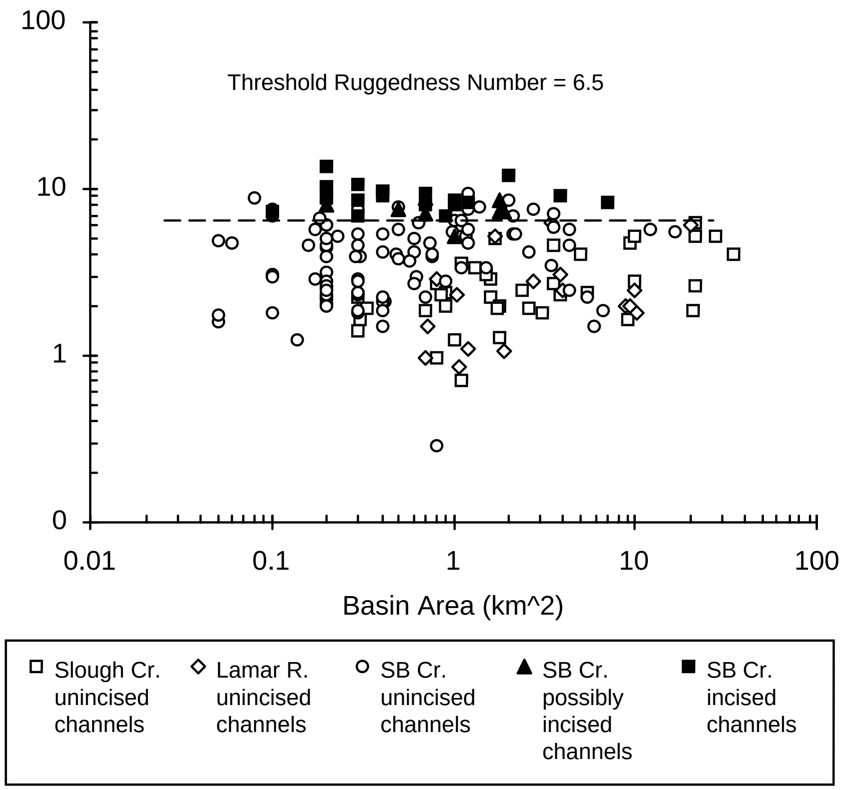


Figure 14. The morphometry of basins in northeastern Yellowstone is a strong control on the state of the associated fan channel (excluding fire-related channel incision). Basins with ruggedness number greater than the threshold value of 6.5 (dashed line) are much more likely to have an incised fan channel (O'Hara, 1994).

Ruggedness number provided the best morphometric discriminant between basins with incised channels and those with unincised channels (Fig. 14). Basins with incised or possibly incised channels had a ruggedness number above 6.5 in 26 of 27 cases; 138 of 154 basins with unincised channels had ruggedness numbers below the threshold value of 6.5. Ruggedness number alone correctly predicts the state of the channel in 91% of all cases. Relations between drainage density and relief ratio of basins also suggest that the greater the drainage density, the lower the relief ratio necessary for incision of fan channels.

Morphometric analysis shows that intrinsic geomorphic differences between tributary basins in large part explain the greater fan channel incision in Soda Butte Creek, thus greater suspended sediment loads and turbidity in this stream, especially in its upper reaches. Several characteristics of the Eocene volcaniclastic bedrock of northeastern Yellowstone result in a high potential for runoff and suspended sediment generation: (1) Poor induration and high rates of physical weathering; (2) its fine-grained weathering products, which are readily suspended in runoff; and (3) low infiltration capacity and high erodibility, resulting in high drainage density. In addition, where poorly sorted debris accumulates on slopes, abundant fines provide matrix for transport of larger clasts in debris flows. Thus, formation of blocky, high-permeability talus slopes that can absorb and retard runoff is inhibited. The potential for generation of turbidity in streams is most fully realized where in steeper and high relief tributary basins, as in Soda Butte Creek.

3.7 Road begins to climb up the side of the Station 22 fan; from this point to mile 5.3, the road crosses an apron-like series of fans at the base of the Abiathar Peak massif.

3.9 Bridge over the large active channel of the Station 22 fan, which is fed from the Abiathar Peak west cirque (Fig. 6). Note ridges of gravel bulldozed up along the channel margins by Park Service road maintenance crews to clear the channel under the bridge.

4.4 **STOP 8: Bridge over incised alluvial fan channel.** A short walk up the south branch of the incised fan channel at this point leads to a large recent intersection point lobe. Down the fan channel, stratigraphic sections (Stas. 8, 9, and 16) and geomorphology on either side of Soda Butte Creek record the interaction of alluvial fans and the axial stream in the middle Holocene and later.

Flash-flood Deposition of an Alluvial Fan Intersection-Point Lobe

A large lobe of recently deposited gravel is present where the incised fanhead channel of the Station 16 fan (Fig. 6) intersects the surface in the midfan area (Fig. 15). This lobe was deposited during flash-flood events from a steep, 0.7 km^2 third-order basin on the west face of Abiathar Peak that was not burned in 1988. In this and similar basins in northeastern Yellowstone, large areas of steep exposed bedrock generate runoff during high-intensity thunderstorm precipitation. The resulting high discharges flush stored sediment from basin channels, but do not typically achieve debris-flow sediment concentrations before reaching the alluvial fan. The dilute flood streamflow incises the fanhead channel, commonly leading to further sediment bulking and deposition of gravel lobes where the channel floor intersects the fan surface. Deposits of these events are generally poorer in fines than those of fire-related events, which have large components of soil-surface silt and clay.

The intersection-point lobe was deposited by at least two flash flood events; fresh deposits were noted immediately after the June 25, 1988 event, but a smaller pre-existing deposit is visible on 1971 air photos. The gravel lobe is located at a decrease in fan slope that may be caused by a shallowly buried bedrock bench or moraine. The stratigraphic sequence is fairly consistent over the main lobe and consists of a lower noncohesive debris-flow to hyperconcentrated-flow unit, 50+ cm thick at the subfan apex, thinning distally to 20 cm or less. A middle unit consists of 15-20 cm of sheetflood pebble gravel. The uppermost unit is a well-imbricated, mostly openwork coarse cobble to boulder gravel which was emplaced in curvilinear bar forms and local steep-fronted lobes. A matrix of silty sand in the lower interstices of this unit appears to represent trapping of suspended sediment from late-stage flow. The uppermost unit appears to have a locally erosional contact on the underlying units. Bouldery deposits at the intersection point diverted later, lower-energy flow into a north sublobe (Fig. 15). The north sublobe is finer (i.e., lacking in boulders), has more subdued bar and swale morphology, and grades distally into sheetflood gravels (cf. Blair, 1987). In the low-gradient distal area, a sheet of stratified moderately sorted silty sand and minor with shallow scour-and-fill features was deposited. Rodent burrowing in thinner areas of the deposit has destroyed most of these structures.

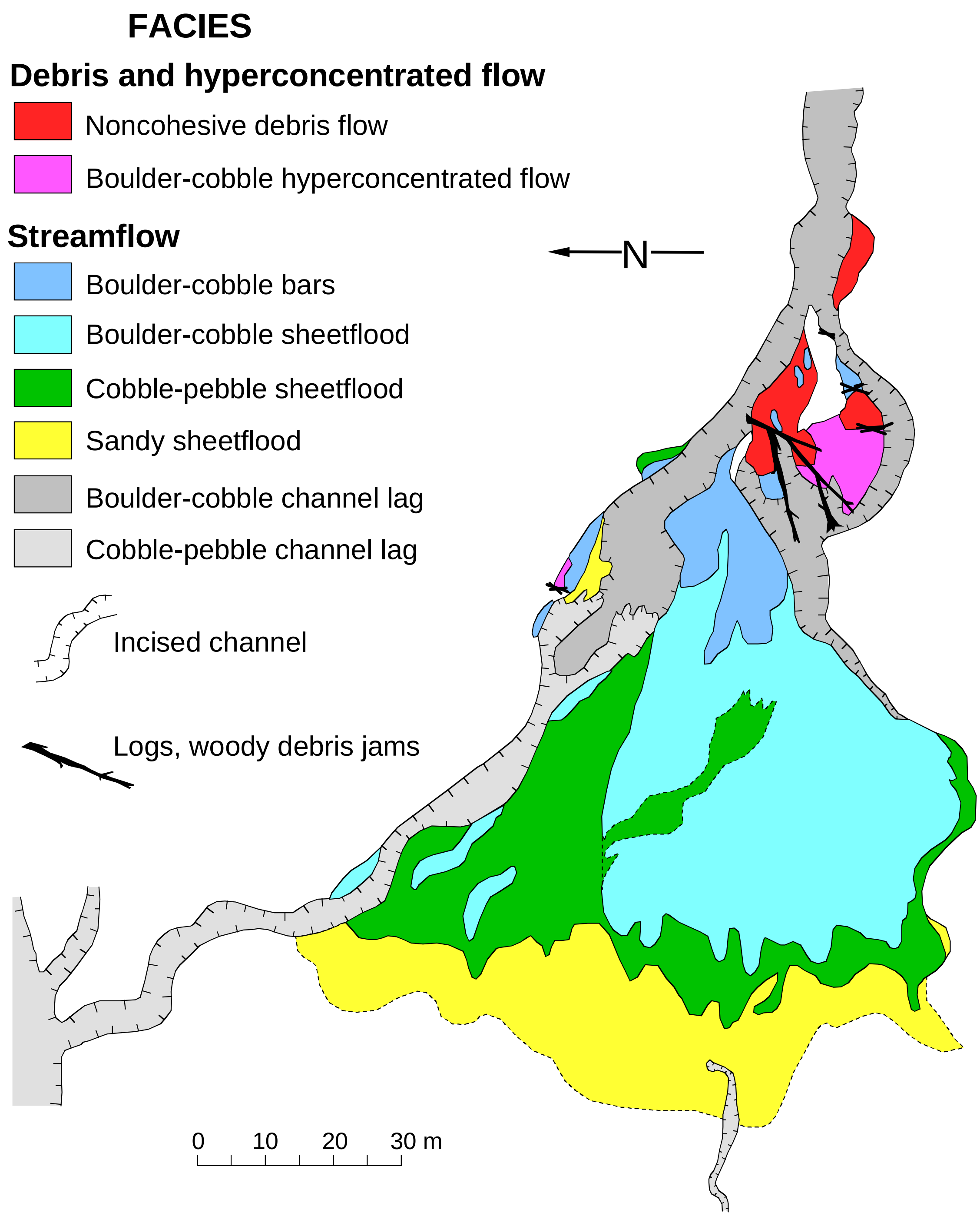


Figure 15. Facies map of an intersection-point lobe deposited below the fanhead channel of the Station 16 fan, middle Soda Butte Creek. Mapped surface facies in some areas thinly mantle differing facies in the underlying deposit.

Maximum Fan Progradation in Middle Soda Butte Creek, 4600-4000 yr BP

Along middle and upper Soda Butte Creek, extensive distal fan surfaces were built between about 4600 and 4000 yr BP and stand several meters above the present floodplain. This period of maximum fan progradation corresponds approximately to the transition between the classic "Altithermal" and "Neoglacial" periods (e.g., Antevs, 1955; Porter and Denton, 1967). At this stop, the proximity of these mid-Holocene fan surfaces shows that the floodplain was strongly constricted by fan toes, and stream power in Soda Butte Creek was apparently insufficient to remove the large mass of sediment. At Station 9 on the west side of Soda Butte Creek (Fig. 6), overbank sediments of Soda Butte Creek contain large angular charcoal fragments dated at 4560 ± 80 yr BP and interpreted to indicate probable fire-related sedimentation (Fig. 4c, Meyer and others, 1995). The overbank sequence is buried by about 4 m of streamflow-facies fan gravel. Fan progradation continued through 4180 ± 150 yr BP, as indicated by charcoal at ca. 150 cm below the fan surface at Station 9, ~30 m to the south. Station 16 is a cutbank exposure in the fan toe from the east valley wall (Fig. 6); distal fan sediments interfinger with and overlie overbank deposits which contain detrital charcoal dated at 4085 ± 55 yr BP. Soda Butte Creek has accomplished no significant net downcutting since ~4000 yr BP in this area, because the dated overbank sediment is less than about 30 cm above the present floodplain elevation. Aggradation of the axial channel may have occurred as the fans subsequently prograded, but no higher channel deposits were identified.

Similarly, at Stations 36 and 56 (see Stop 5) in upper Soda Butte Creek, and Station 14 in Lodgepole Creek (Clarks Fork drainage; Fig. 6), progradation of distal fan sediments over axial stream floodplain areas occurred shortly after ca. 4600 yr BP and continued until at least 4000 yr BP. This major period of fan progradation suggests flushing of stored sediment from tributary basins, probably by summer thunderstorm-generated flash floods. Stratigraphic evidence suggests that some of this fan sedimentation was fire-related. At the same time, stream power in Soda Butte Creek and other axial streams was insufficient to remove the accumulating distal fan sediment, suggesting reduced snowmelt runoff.

4.8 Bridge over the incised alluvial fan channel of Stations 5 and 6 (Meyer et al., 1995).

5.1 **STOP 9: Station 12 alluvial fan.** The bridge over the incised channel of this fan is the southernmost of several such crossings in middle Soda Butte Creek. Station 12 (Fig. 6) is on the north wall of the channel at a sharp bend about 250 m above the bridge. Fire-related debris flows at about 260-290 cm and 370-420 cm below the fan surface have ^{14}C ages of 2180 ± 80 yr BP and 2240 ± 70 yr BP. The upper of these units is a good example of a charcoal-rich, gravel-poor debris flow runout deposit. A few meters upstream, a burn surface at ~160 cm depth was dated at 1950 ± 80 yr BP. These ages demonstrate rapid fan aggradation, partly in response to forest fires. A number of other fans in the Soda Butte drainage experienced fire-related sedimentation and rapid aggradation from about 2200-1800 yr BP (e.g., Station 27, Stop 4), as did a small fan in Gibbon Canyon in west-central Yellowstone (Meyer et al., 1995).

5.3-5.5 Landslide debris with boulders of volcaniclastic breccia from the south Abiathar Peak massif.

5.5 **STOP 10: Soda Butte floodplain above Icebox Canyon.** Road turnout at upper end of a large floodplain meadow. The gravelly chute nearest the road dates from the 1950 dam-break flood, and tailings deposits are present in low-energy sites on this surface (See Stop 11, tree-ring dating of floods along Soda Butte Creek, and Figure 18a, map of flood surfaces in the Stop 10 area). Julie Stoughton and Andrew Marcus studied the relationship between grass densities and metal concentrations in floodplain sediments at this site (Marcus et al., this volume). Downstream, the large alluvial fan of Station 4 extends onto the floodplain, and across Soda Butte Creek, a cutbank in a small secondary fan is visible (Station 15). This fan is fed by a channel that extends through a bench of sandy late Pinedale kame(?) sediments (Pierce, 1974a).

Station 15 Secondary Fan

At Station 15, fine distal fan sediments overlie axial stream overbank deposits in a secondary fan toe cutbank exposure (Fig. 6). Detrital charcoal fragments from near the top of the overbank facies have an age of 1880 ± 50 yr BP. This age corresponds to the time of T3 terrace formation in the lower Soda Butte valley, and indicates that floodplain widening was occurring at approximately the same time in both areas (see discussion of terrace-forming processes following Stop 17). Greater average discharge and stream power in Soda Butte Creek would allow fan toes to be eroded back and the floodplain to expand. Decreased stream power would allow fans to prograde over former floodplain areas, as at Station 15.

The next overlying dated horizon is a burned-in-place layer approximately 2 m above the floodplain-fan transition, which yielded a ^{14}C age of 175 ± 50 yr BP. This age corresponds to two possible calibrated age ranges of 1658 -1694 AD and 1729-1816 AD (1 σ ranges); 1943 AD and younger possible ages are rejected on the basis of significant A horizon development on the surface ca. 120 cm above this layer. Both age ranges bracket times of large fires in Yellowstone, as identified by tree-ring (Barrett, 1994) and lake-sediment studies (Millspaugh and Whitlock, 1995).

Age Range of Charcoal in a Fire-related Debris Flow, Station 4

In the study of Meyer et al. (1995), most ^{14}C age determinations for fire-related debris flows were conducted on a large sample of coarse angular charcoal fragments. To examine the age range of charcoal in a single fire-related debris-flow and test for reworking of charcoal, five individual fragments from a single debris flow at Station 4 (Fig. 6) were dated by AMS techniques. These samples gave ages of 2825, 2480, 2480, 2525, and 2545 yr BP (AA-7210 through AA-7214), all with 1 σ errors of 55 yr. All five ages cannot be considered to represent a single event, as they are significantly different from their mean (2570 ± 25 yr BP). The latter four ages, however, are indistinguishable from their mean (2508 ± 28 yr BP) at the 95% level of confidence (Ward and Wilson, 1978).

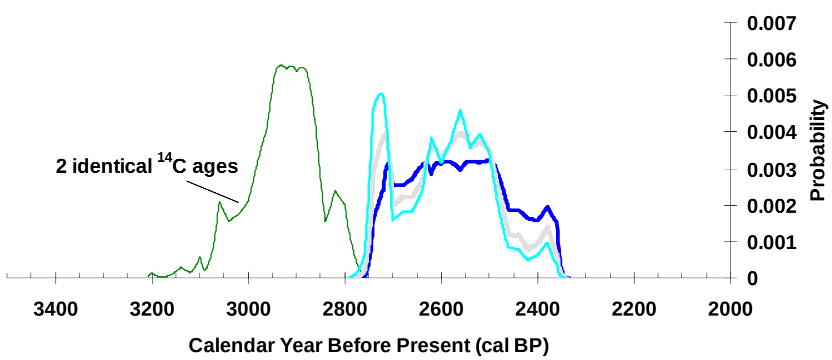


Figure 16. Calibrated age spectra for five ^{14}C-dated charcoal fragments from one fire-related debris flow unit. Four of the five ages are strongly overlapping. A "plateau" in the calibration curve (Stuiver and Reimer, 1993) over this time interval increases the uncertainty in the calibrated ages.

Probability distributions (age spectra) for the calibrated ages also show very close correspondence for four of the five ages (Fig. 16), thus the four dated charcoal fragments were probably produced in a single forest fire. Trees in northeastern Yellowstone are mostly less than 300 years old (Barrett, 1994), and even in the intense 1988 fires, only the young outer wood was charred on most trees. Older wood from inner rings and dead timber may be charred and incorporated in debris flows, however, and some charcoal may be reworked. Although aggregate sample ages are subject to systematic errors from inclusion of older fragments, the five test dates suggest that such errors are relatively small.

5.6-6.1 Road crosses the distal portion of the large fan of Station 4 (Fig. 6).

6.1 Lower Bridge over Soda Butte Creek.

6.3-6.8 Landslide debris with boulders of Eocene volcaniclastic breccia from Barronette Peak massif.

6.4-6.5 View straight ahead of small north-facing cirques on The Thunderer (10,543 ft).

6.8 Turnout on high floodplain or low terrace of Soda Butte Creek. Flood bars and low terraces are visible across the stream.

7.1-7.9 Icebox Canyon, so named because of "frozen waterfalls" from seeps and springs that persist well into the summer in this narrow, shaded gorge in Eocene volcaniclastic rocks.

7.7 Fan(?) gravels in roadcut.

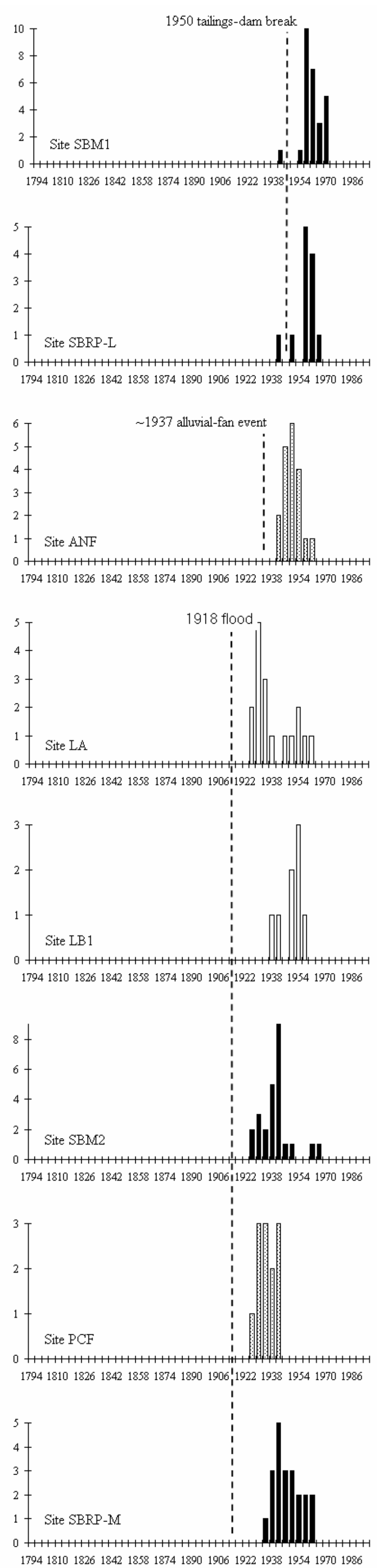
7.9 **STOP 11: Thunderer trailhead.** Large turnout at the mouth of Icebox canyon and head of Round Prairie. Walk a short distance down the Thunderer trail to the ford across Soda Butte Creek for discussion of dendrochronology and flood history.

Changes In Flood Magnitudes and Processes in Northeastern Yellowstone

(Grant Meyer, Matthew K. Bingham, and Eric D. Simpson, Dept. of Geology, Middlebury College)

A notable feature of floodplains and alluvial fans in the Lamar and Soda Butte drainages is the presence of distinct "even-age" stands of conifers which appear to have colonized gravelly flood bars after deposition. This observation prompted us to investigate tree-ring methods for dating of flood events (e.g., Helley and LaMarche, 1973; Hupp, 1988). We combined dendrochronology with paleohydrological techniques of discharge reconstruction to investigate changes in flood magnitudes over the last 150 years. Anecdotal records exist for floods on Soda Butte Creek in June 1950 (produced by the McLaren tailings dam failure) and on the Lamar River in June 1918 . The highest discharge on the Yellowstone River at Corwin Springs and Billings, Montana, also occurred with the June 1918 flood, which was produced by rain on melting snow (U.S. Geological Survey, 1991). These floods produced broad gravelly bars and overbank gravel deposits. The age of conifers growing on these bars provides a minimum age for floods. Where dates of floods are known or probable (i.e., 1950 and 1918), the age of the oldest trees postdates the flood by about 10 years (Bingham and Meyer, 1994; Simpson and Meyer, 1995) (Fig. 17). This lag time reflects germination time and the difficulty of obtaining the first few growth rings by coring trees with an increment borer, and may vary by several years between different sites.

Using a 10-yr lag time, tree-ring data give evidence for the 1950 and 1918 floods on the Soda Butte Creek mainstem, as well as a larger(?) flood in the early 1870s (Simpson and Meyer, 1995) (Fig. 17). Dendroclimatic studies in Yellowstone identified the spring of 1873 as an anomalously wet period in northeastern Yellowstone (Douglas and Stockton, 1975), thus we use this year as a first approximation for the date of the flood. At site SBRP in upper Round Prairie (this stop), extensive gravel bars were deposited where the 1918 and ~1873 flows became unconfined and spread over the broad floodplain just below Icebox Canyon (cf. Ritter, 1975) (Figs. 18b, 19). Although the effects of these floods overlap to some degree, later flood deposits tend to be inset within and slightly below earlier deposits, producing distinct, tree-ring datable flood surfaces, and suggesting net channel incision during floods.



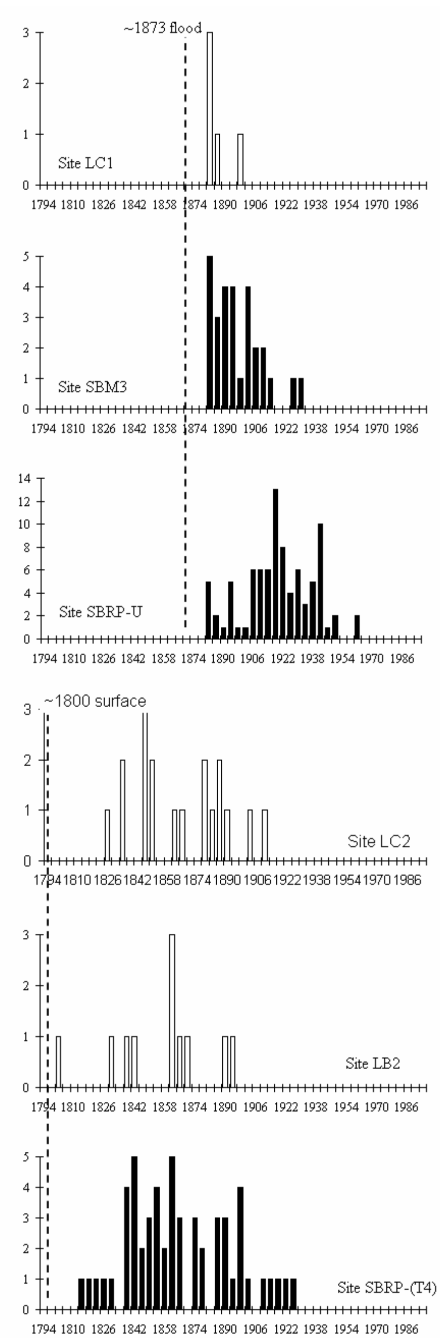
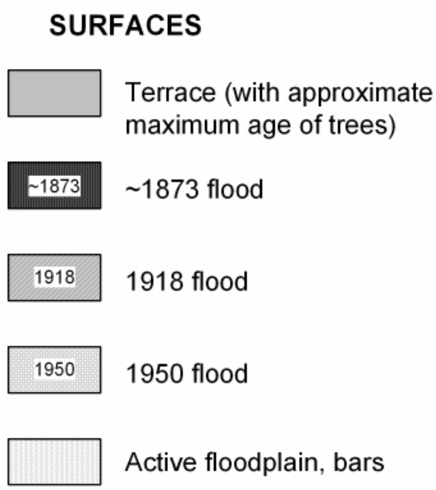
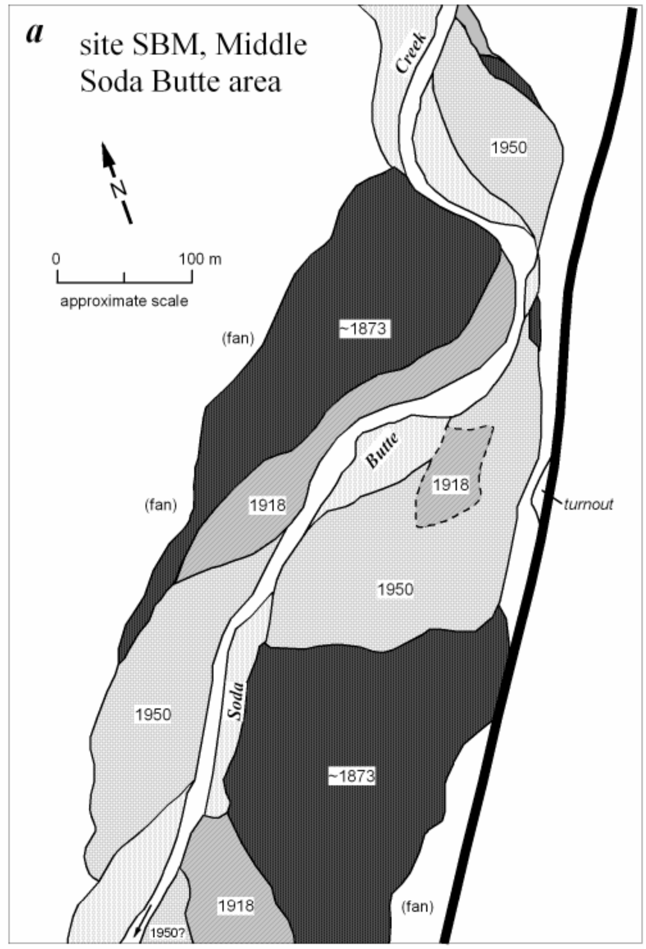
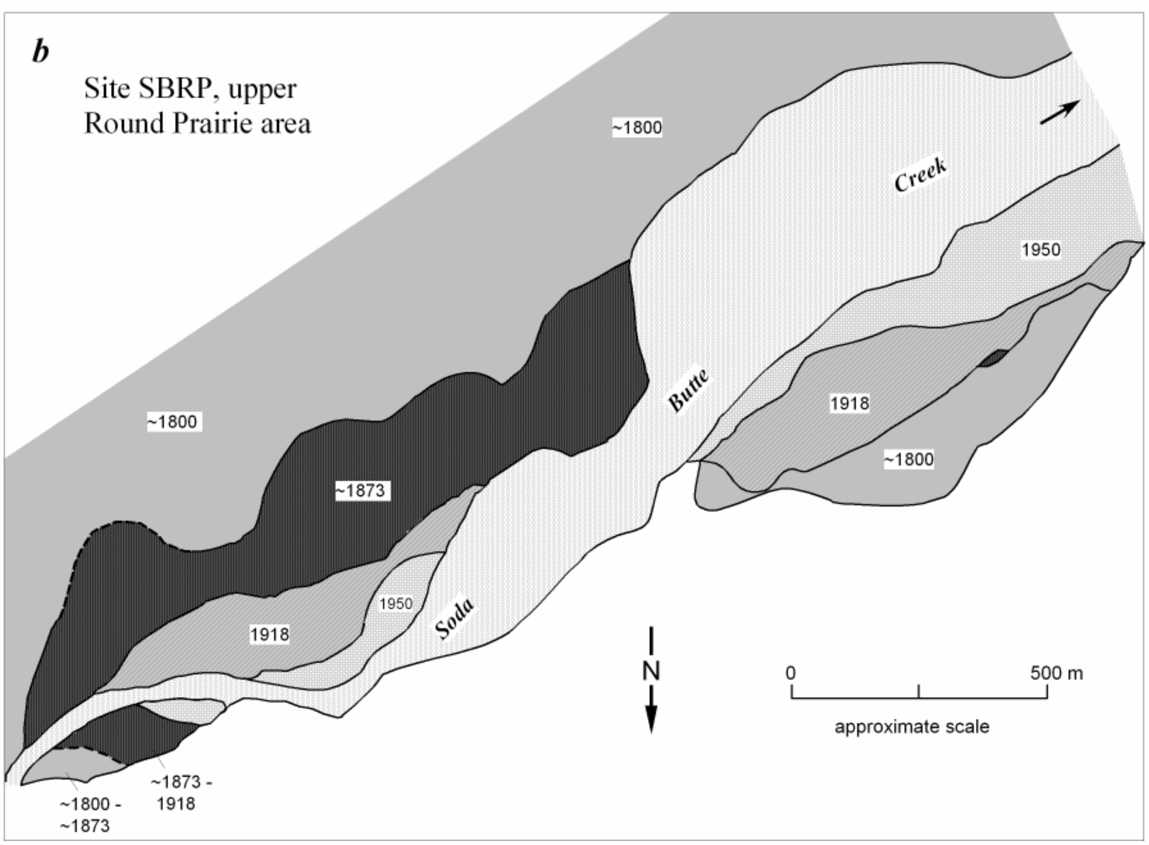


Figure 17. Histograms of tree ages on flood surfaces in the Soda Butte Creek and Lamar River drainages. Black bars = mainstem Soda Butte Creek, gray bars = Soda Butte tributaries, and open bars = Lamar River. Sites: SBM = middle Soda Butte (Fig. 18a); SBRP = Soda Butte at Round Prairie (Fig. 18b); L = Lamar River above the Soda Butte confluence; ANF = Abiathar north fan; and PCF = Pebble Creek fan. Note ~10-yr lag time between flood events and the oldest tree ages. 1950 flood surfaces have a few older trees which survived the flood. The significance of the maximun age of trees on the highest (~1800) surfaces is unclear.

Figure 18. Map of floodplain and flood bar surfaces along Soda Butte Creek at ***a,*** site SBM in the middle valley, approximately 1 km north of the lower bridge on the Northeast Entrance road (Stop 10), and ***b,*** site SBRP, at the head of Round Prairie, just downstream from Icebox Canyon (Stop 11). Flood surfaces were mapped using elevation, surface morphology and sedimentology, and minimum age as determined by dendrochronology (Bingham, 1994; Simpson, 1995).







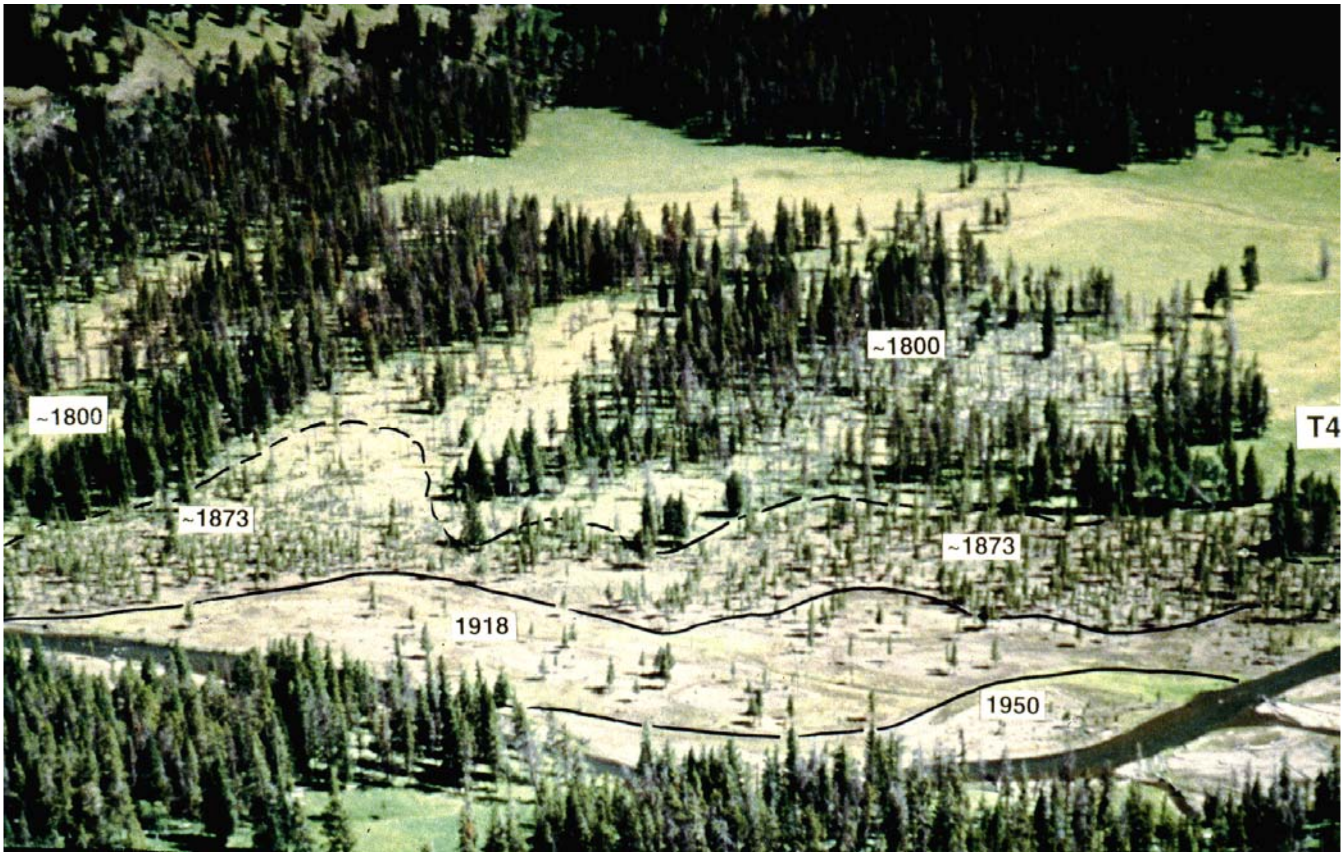


Figure 19. Photograph of upper Round Prairie (upper part of site SBRP) looking southeast, showing contrasts in density and height of trees on gravelly flood surfaces of different ages; compare to Figure 18b. The ~1800 surface may be correlative with the T4 terrace of the lower Soda Butte Creek valley.

The highest surface at site SBRP shows elongated stands of conifers that radiate from the head of Round Prairie, a pattern that may be controlled by the texture of underlying fluvial deposits (Fig. 19). This surface supports trees as old as ~1815 (Fig. 17) and may correlate to the T4 terrace of the lower Soda Butte valley. In contrast to younger surfaces, it has significant fine overbank sediment. Several trees on the slopes immediately adjacent to the floodplain date from 1750-1800, indicating that the maximum age of trees on the highest surface is unlikely to be due to forest fire(s), but the significance of the tree ages is unclear. The maximum age may relate to (a) flood deposition of overbank gravels suitable for germination of conifers, (b) decline of the floodplain water table allowing conifers to germinate in areas that were previously too wet for tree growth, or (c) other unknown environmental and biological factors.

Dendrochronology of trees colonizing distinct flood gravel surfaces along middle Soda Butte Creek, about 2.5 km above Icebox Canyon also gives evidence for floods in 1950, 1918, and ~1873 (site SBM, Figs. 17, 18a). The 1950 flood was apparently of greater relative magnitude and geomorphic effect here than in Round Prairie, as would be expected for this dam-break flood; the major tributary of Amphitheater Creek enters between these sites, and would not have been affected by the dam failure. Tree-ring data show that bars on the Pebble Creek fan at its confluence with Soda Butte date to 1918 (site PCF, Fig. 17) (see Stop 13). No evidence of an ~1873 flood event was observed at this locality.

Dendrochronology also indicates that large flood bars along the Lamar River ~3 km upstream of Soda Butte confluence formed in 1918 (sites LA and LB1, Fig. 17). The oldest trees on the highest floodplain surface of the Lamar River also date to near 1800, suggesting a common environmental control with tree growth on the highest surface in Round Prairie (sites LC2 and LB2, Fig. 17). Evidence for a flood in the early 1870s on the Lamar is limited to a small area inset just below the highest surface (site LC1, Fig. 17).

Discharge reconstructions for the 1918 flood were made using (1) the slope-area method (Benson and Dalrymple, 1967), (2) a simplified slope-area method which eliminates roughness by correlation with slope (Riggs, 1976) and (3) average velocity estimated from maximum size of flood-transported clasts (Costa, 1983), along with geomorphic indicators of flood stage. Imbrication was used as evidence of flood transport of the largest clasts. A primary source of potential error lies in the nature of channels at discharge reconstruction sites: the Soda Butte channel in Round Prairie has boundaries entirely in alluvial deposits, and the Lamar channel is bounded by bedrock only on one bank. The Pebble Creek site (in the canyon above the campground, 1 km upstream of the Soda Butte confluence) has bedrock-confined banks, however, the floor of the channel is composed of boulder gravel which may have scoured during peak flow.

To account for uncertainties in scour and fill during floods as well as the range of possible flood stages, a range of channel cross sections were constructed representing minimum and maximum possible cross-sectional area. A midrange cross-section was also drawn as the "best" estimate given field observations and flood depths indicated by the maximum size of transported clasts (Costa, 1983). The resulting minimum, maximum, and midrange estimates are presented in Table 1.

Peak discharge estimates at the study sites are: Lamar River, 17600 ± 2300 cfs; Soda Butte Creek, 6700 ± 1200 cfs; and Pebble Creek, 2250 ± 360 cfs. These estimates define a consistent basin area to peak discharge relation that is similar to the average relation for 100-yr floods in the Yellowstone region (Fig. 19). The 1918 discharges, however, are substantially greater than 100-yr flood flows predicted by analysis of regional gage records from the last ~35 years. The lack of similar high discharges in more recent decades suggests a decline in trunk-stream flood magnitudes, also supported by Yellowstone River gage records from 1911 to present. Prolonged heavy rain on melting isothermal snow during spring to early summer is responsible for the largest floods on trunk streams in this area (Church, 1988; U.S. Geological Survey, 1991). A heavy snowpack may persist into the summer and enhance the probability of such an event. Since 1895, however, winter precipitation has decreased and summer temperatures have increased in the Yellowstone area (Balling et al., 1992a, 1992b).

TABLE 1: PEAK DISCHARGE ESTIMATES FOR THE 1918 FLOOD (ft^3/s) IN THE UPPER LAMAR SYSTEM.

Method	Estimate	Lamar R.	Soda Butte-Rnd. Prairie[1]	Pebble Cr. Reach A	Pebble Cr. Reach B
Slope-Area	Min	18300	3100	1500	1400
	Mid	20700	5900	2100	2400
	Max	23100	10300	2700	3500
Simplified Slope-Area	Min	15300	5400	1500	1100
	Mid	17700	8200	1800	1700
	Max	20100	11400	2100	2300
Threshold Velocity	Min	14900	4900	2400	2000
	Mid	16000	6400	2600	2400
	Max	17200	7800	2900	3300
Average[2]	Min	15900	4600	2000	1600
	Mid	**17600**	**6700**	**2300**	**2200**
	Max	19400	9300	2700	3100
Std. Dev. of Midrange Aves.		2300	1200	360[3]	

[1] Manning equation substituted for slope-area method at this locality
[2] Mean of results from two slope-area methods averaged with threshold-velocity result for each site.
[3] Standard deviation of 6 averages from Reach A and Reach B.

Although large overbank floods on trunk streams have been rare in northeastern Yellowstone in the last 60 years, recent observed events and initial tree-ring dating efforts on small tributaries of Soda Butte Creek suggest that flash flooding in small, steep tributary basins has been quite active during this period. Floods that postdate the mainstem floods occurred (1) on an alluvial fan in ~1937 (site ANF, Fig. 17) and (2) in a number of unburned basins during an intense thunderstorm in late June, 1988 (see Stops 6 and 8). We hypothesize that warming evident in instrumental climate records in Yellowstone has been accompanied by an increase in the intensity and/or frequency of convective storm precipitation, leading to an increase in flash flood activity. An increase in summer precipitation since 1895 is apparent, but not statistically significant (Balling et al., 1992a). Dominant flood-generating processes appear to have changed from prolonged frontal-storms and snowmelt runoff, which produce widespread floods in trunk streams, to localized intense thunderstorms, which produce floods in small steep basins with large areas of runoff-generating bare bedrock. Changes in climate and streamflow in Yellowstone over the last century are broadly associated with a global(?) transition toward warmer conditions at the end of the Little Ice Age ca. 1900 (e.g., Grove, 1987; Bingham and Meyer, 1994).

Although several lines of evidence suggest a cooler period in the Yellowstone region from about AD 1300 to AD 1900 (e.g., Hadly, 1990; Meyer et al., 1992, 1995, and this volume; Millspaugh and Whitlock, 1995) little detailed paleoclimatic information is presently available on the nature of the Little Ice Age in Yellowstone. Minimal fire-related sedimentation (Meyer et al., 1995) and large debris avalanche(s) (see Stops 6 and 18) occurred during this time in northeastern Yellowstone, consistent with a cooler, effectively wetter climate.

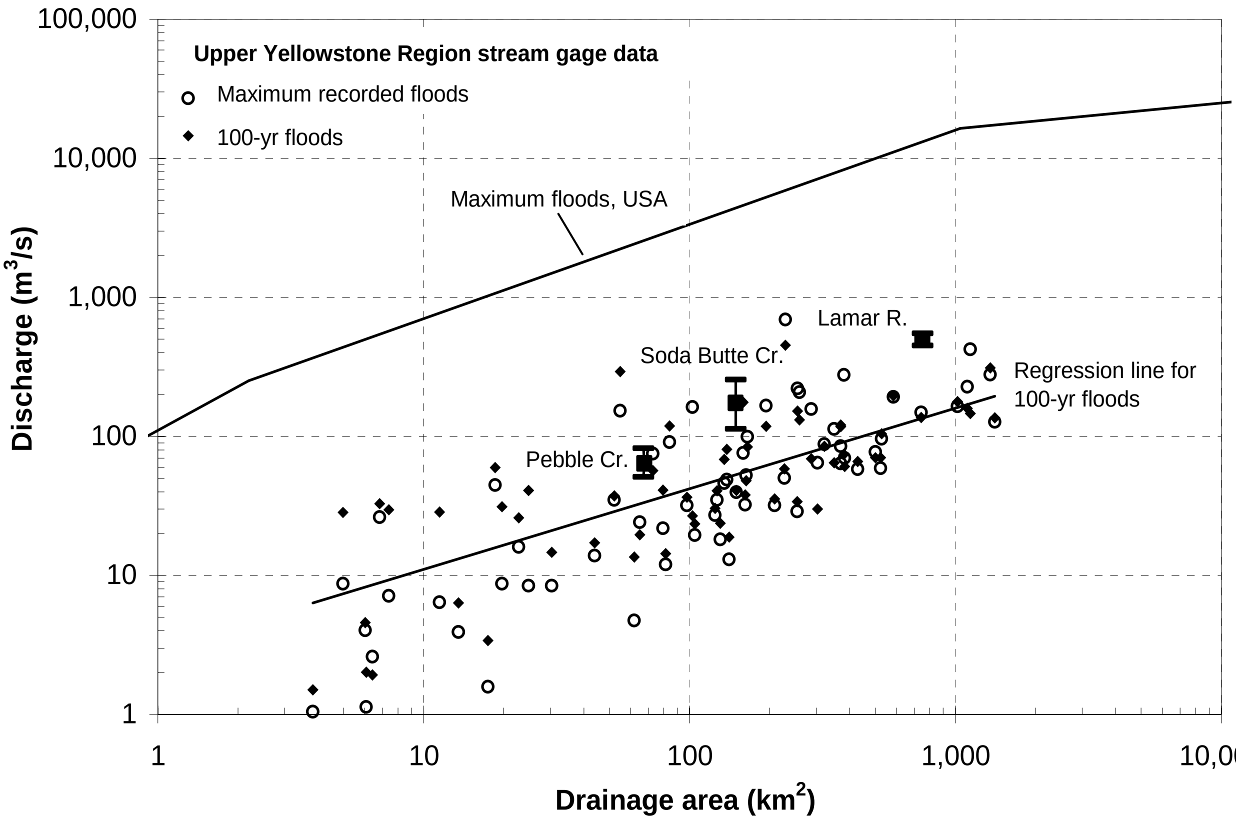


Figure 20. Reconstructed peak discharges for the 1918 flood in the Lamar River system versus drainage basin area (solid squares, with error bars indicating range of estimates). Also plotted are maximum recorded flood discharges in the upper Yellowstone River basin and adjacent areas of Montana (solid circles), and a curve fit to 100-year flood estimates based on standard log-Pearson type III analyses of stream gage records (from Omang et al., 1986). Most of the gage records in this region are only a few decades in length. The 1918 flood peaks are substantially higher than the average 100-year flood in relation to basin area, but are well within the envelope defined by the largest recorded discharges within the upper Yellowstone region.

8.1 **STOP 12: Small alluvial fan of Stations 23-24-34.** The road crosses this small, steep alluvial fan in a grassy meadow. The fan is strongly confined between morainal forms in its upper part and between outcrops of Madison Limestone and late Pinedale(?) silts and sands below the road. The upper basin of this fan contains steep slopes of highly erodible and unusually clay-rich volcaniclastic rocks. At Stations 23 and 24 on the upper fan (Fig. 6), fire-related debris flows dated at 1170 ± 80 and 965 ± 50 yr BP are buried by >3 m of sediment. At Station 24, an unburned buried log at 200-280 cm depth has an age of 400 ± 60 yr BP on outer wood. A burn surface at ~1.5 m depth is dated at 40 ± 50 yr BP and has a calibrated 2σ age range between ca. 1680 AD and present (Stuiver and Reimer, 1987). Station 34 is a cutbank of Soda Butte Creek in the fan toe. This unusual section of faintly stratified silty clay contains several charcoal-rich layers, but no discrete burn surfaces were clearly identifiable. The charcoal is probably detrital material in fine-grained facies of fire-related debris flows from the forested upper basin, because clay-rich deposits of the distal fan support only herbaceous plants

(Despain, 1990). Dates on charcoal concentration zones within this section include 1830 ± 55 yr BP at 30-45 cm depth, 8700 ± 110 yr BP (180-185 cm), and 9360 ± 75 yr BP (~275 cm). The latter two ages provide the only record of probable fire-related sedimentation on fans in the study area before 8000 yr BP (Meyer et al., 1995).

Late Pinedale lake/flood deposits? Just downstream of Station 34, a high cutbank exposes an interesting stratigraphic section with contorted beds of silty clay to fine sand at the base, overlain by a ~2 m-thick channel-like body of coarse sands with very continuous laminae, and low-angle wavy cross-stratification suggesting rapid subaqueous deposition. The sands are sharply overlain by an additional few meters of silt with some thin graded and rippled beds and much soft-sediment deformation. This section has not been studied in detail. It may represent deltaic deposits of a lake in Round Prairie, perhaps ice-dammed in the Slough Creek area (see Stop 20) or moraine or landslide-dammed in the Trout Lake area (see Stop 14). Alternately, some observers have suggested that the deposits are slackwater sediments of a large flood, which would require a large volume of water to fill Round Prairie to the required depth. A combination of these hypotheses invokes large sediment-laden flood(s) entering a lake. The flood may have originated from a glacial outburst, or breaching of a large landslide dam in upper Soda Butte Creek.

8.8 **STOP 13: Pebble Creek bridge.** The maximum age of lodgepole pines on the flood bars below the bridge indicate formation in the June 1918 flood; no evidence is seen for a ~1873 event (site CF, Fig. 17). The pattern of flood bars here shows that the bridge postdates the 1918 flood, which washed out the road in several places. Discharge estimates for the 1918 flood on Pebble Creek were made in the narrow canyon through the Mississippian Lodgepole Limestone just upstream of the Pebble Creek campground. Peak discharge in Pebble Creek was lower in relation to basin area than in Soda Butte Creek and the Lamar River (Fig. 20). Flood potential may be lower in Pebble Creek due to greater forest cover, lesser exposed bedrock, and slightly lower relief. Average relief ratio for tributary basins in Soda Butte Creek above Pebble Creek is 0.59 ± 0.25 (O'Hara, 1994), and 0.51 ± 0.33 for Pebble Creek basins. These means are not significantly different at the 95% confidence level, but the highest relief basins in middle Soda Butte also have large areas of runoff-generating exposed bedrock.

9.1 North edge of Trout Lake debris avalanche lobe to west with large boulders of poorly indurated Eocene volcaniclastic breccia.

9.6 Turnout on east side of road. From this area on to the south, the toe of the Trout Lake landslide has failed in a series of large slumps. These slumps also involved Pinedale glaciofluvial gravels, which are exposed in the roadcut to the west of the turnout. Only low terraces are present along Soda Butte Creek in Round Prairie (for example, near the turnout and along the opposite valley margin), probably in part because slumps dammed the stream and raised base level in this area (see following sections).

9.7 Steep, bouldery channel of Soda Butte Creek is constricted between slumped toe of Trout Lake landslide on west side and toe of large alluvial fan on east side. Some slump material is found on the east side of Soda Butte Creek several meters above the channel, indicating temporary damming of the stream. The large roadcut on the west exposes debris-avalanche deposits with large volcaniclastic boulders, overlying Pinedale glaciofluvial gravel, sand, and silt; these units are tilted by slumping.

10.0 **STOP 14: Trout Lake trailhead.** Late Pinedale recessional moraines are present in this area of the Soda Butte Creek valley (Fig. 21). On the west side of the valley, moraines bearing granitic gneiss erratics are complexly intermingled with a large late Pinedale debris avalanche (herein termed the Trout Lake Landslide) originating in the bowl-shaped headscarp area on the east face of Mount Hornaday.

Trout Lake Landslide; Slumping of the Landslide Toe and Damming of Soda Butte Creek

Trout Lake lies within the debris-avalanche area about 0.5 km north of the road turnout. The large, rounded, and steep-sided Trout Lake depression displays unusual morphology for a debris avalanche deposit, however, and contrasts with well-defined radial ridges on the landslide lobe to the southwest (Fig. 21). The lake is a kettle-like feature, suggesting that the landslide may have been emplaced partly onto stagnant ice (Pierce, 1974a). As another complicating factor, the avalanche debris probably incorporated tills from the headscarp area. Outwash deposits from this terminus occur underneath and along the toe of the debris avalanche south of Trout Lake, but are disrupted by later slumping and are not traceable downvalley.

Large rotational slump blocks have downdropped and extended the toe of the Trout Lake landslide from just south of Trout Lake and Buck Lake to the present course of Soda Butte Creek (Fig. 21). Slumping also involved Pinedale kame or outwash gravels (pku of Pierce, 1974a) along the valley margin south and southwest of Trout Lake. A number of slump masses are elongated parallel to their rotational axis and are similar to the "Toreva-blocks" of Reiche (1937). Topography in this area superficially resembles a complex set of braided channels when viewed on aerial photographs, but the apparent "channels" lack continuity and are actually elongate closed depressions. Although these gravels appear relatively stable, the potential for slumping may have been enhanced by several factors: (1) stresses induced by the unstable landslide deposits above; (2) undercutting by Soda Butte Creek; (3) high pore pressure due to groundwater under a substantial hydraulic head from Trout Lake; (4) the presence of underlying fine sediments, as are seen in the roadcut north of the Trout Lake trailhead; and (5) possibly, underlying strongly weathered, clayey pre-Pinedale deposits, as are exposed in a cutbank on the east side of Soda Butte Creek in this area.

Slump blocks extended across the relatively narrow valley in this area, forming a dam against the moraine ridges and fan toes on the southeast side of the valley (Fig. 21). A complex of channels and local flood terraces were created by overtopping and incision of the slump mass. These features are best preserved near the Trout Lake trailhead parking area, and ~0.8 km farther downvalley, where a narrow channel (presently containing several lodgepole pines) converges with the Northeast Entrance road (Fig. 21). This channel probably follows an arcuate slump depression. The flood terraces in this lower area show a nested morphology; as each lower, later terrace was formed, the stream gradient was reduced, flow became progressively more confined within higher, earlier flood deposits, and the point of flow divergence from the inset channel moved progressively farther downvalley. These relations are typical of flood terraces formed by breaching of landslide dams (Turner and Locke, 1990) and flood-generated fan deposits in general (e.g., Blair, 1987). The flood surfaces project to convergence with the T3 terrace, and flood channel 5 (the lowest and last surface bearing the trees) diverges directly onto the T3 terrace (Fig. 21).

Mid-Holocene Fan and Fluvial Interaction and Mazama Ash Locality

Mid-Holocene progradation of alluvial fans from the southeast side of the valley forced Soda Butte Creek northwestward against the toe of the Trout Lake landslide and adjacent glacial and fluvial sediments (Fig. 21). Undercutting was thus probably factor in slumping of these materials. Progradation of the southern of the two fans which impinge on Soda Butte Creek in this area is younger than 5940 ± 240 yr BP at Station 44 (Fig. 6), and continued after 5290 ± 70 yr BP.

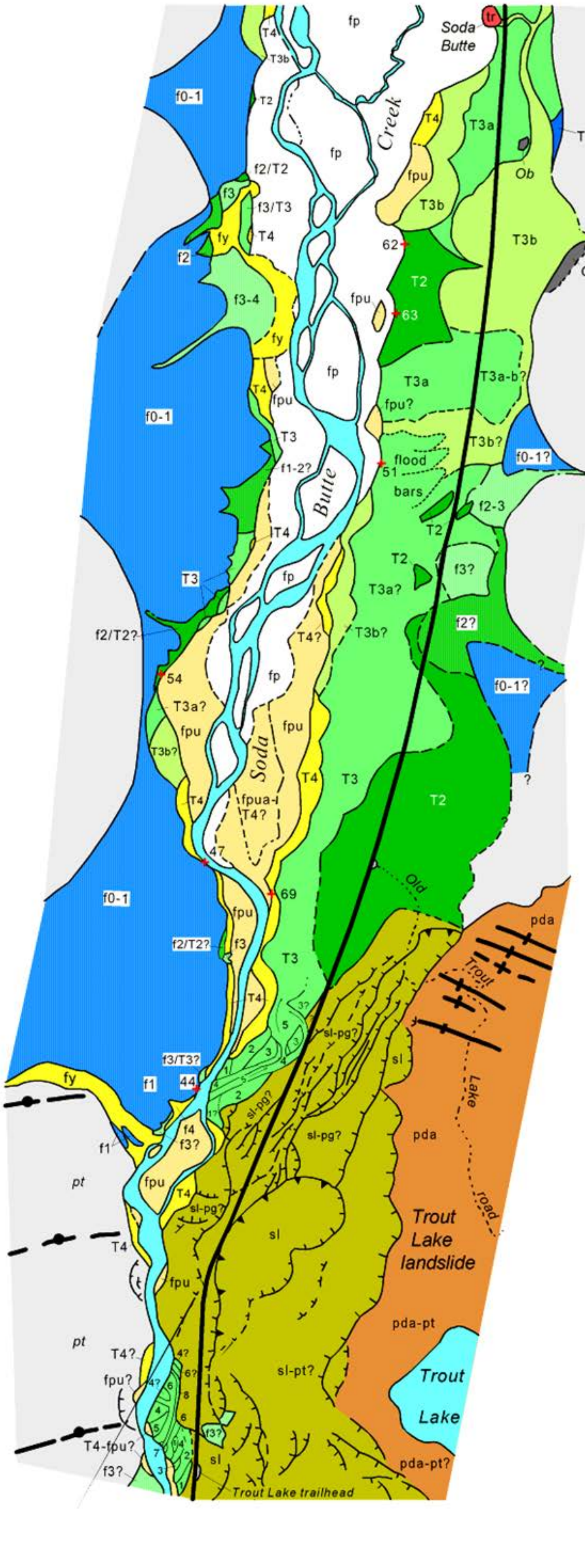
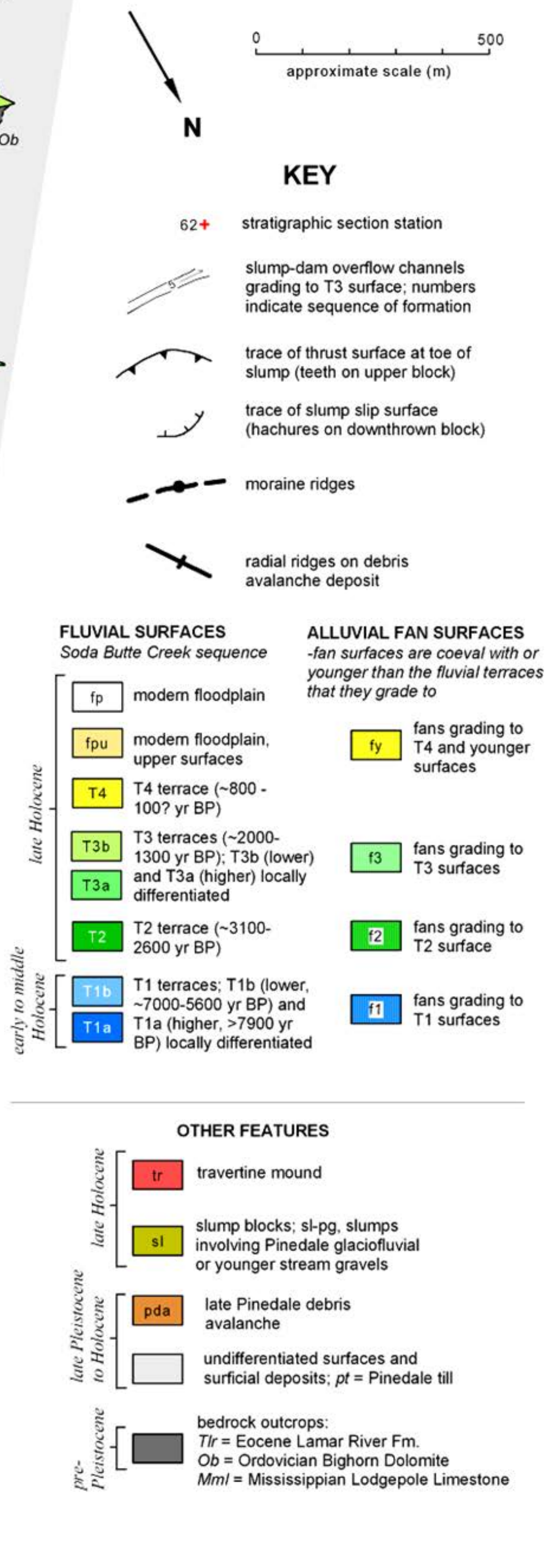


Figure 21. Geomorphic map of the lower Soda Butte Creek valley from the Trout Lake area to the Soda Butte spring (airphoto base, uncorrected).



Slumping forced Soda Butte Creek back eastward, causing the erosion and exposure of the fan toe. At Station 44, distal fan gravels bury a fluvial overbank sequence containing a ~0.5 cm-thick layer of tephra identified by microprobe analysis as Mazama ash (D. Johnson, written communication, 1990; Meyer, 1993) (Table 2). The Mazama ash from the climactic eruption at Crater Lake, Oregon is widely distributed over the northwestern U.S., although the eastern limit of its known occurrence is in eastern Yellowstone National Park (e.g., Waddington and Wright, 1974; Sarna-Wojcicki et al., 1983). The Mazama distal fall tephra at this locality is a very light gray (10YR7/2 to 8/2) layer in silty Soda Butte Creek overbank sediments, about 0.5 cm or slightly greater in thickness, and more or less continuous across the width of the exposure. The ash is fairly "clean" and appears to be an *in situ* fall tephra that was buried and preserved in the low-energy overbank environment. A widely cited, relatively precise radiocarbon age for Mazama ash is 6845 ± 50 yr BP (four-sample weighted mean; Bacon, 1983), although other possibly accurate ages fall between about 6900 and 6400 yr BP (e.g., Brown and others, 1989). At Station 44, Mazama ash is bracketed by ^{14}C ages of 6930 ± 60 yr BP and 5940 ± 240 yr BP on probable *in situ* charcoal in weak, slightly bioturbated A horizons (Figure 4d, Meyer et al., 1995). These relations support the accuracy of the radiocarbon dates and show that fluvial overbank deposition at Station 44 is of T1b terrace age.

TABLE 2. RESULTS OF ELECTRON MICROPROBE ANALYSIS (IN WT. % OF OXIDES) OF SHARDS IN SAMPLE 90GM-117 FROM STATION 44, IDENTIFIED AS MAZAMA ASH.

Shard	Fe_2O_3	Na_2O	K_2O	MgO	CaO	TiO_2	Al_2O_3	SiO_2	Cl	NSF[1]
1 2.46	5.16	2.62	0.44	1.61	0.45	14.47	72.60	0.19	1.00	
2 2.43	5.07	2.78	0.53	1.60	0.44	14.37	72.61	0.18	0.99	
3 2.58	5.11	2.59	0.45	1.63	0.45	14.36	72.67	0.16	0.99	
4 2.35	4.84	2.70	0.46	1.65	0.41	14.69	72.73	0.17	1.00	
5 2.34	5.09	2.76	0.45	1.65	0.39	14.41	72.75	0.17	0.99	
6 2.35	5.05	2.60	0.45	1.68	0.40	14.39	72.78	0.31	1.01	
7 2.47	4.96	2.63	0.46	1.68	0.41	14.40	72.83	0.16	1.00	
8 2.63	4.97	2.62	0.42	1.72	0.40	14.23	72.85	0.15	1.00	
9 2.41	4.94	2.68	0.46	1.67	0.47	14.37	72.86	0.13	1.00	
10	2.31	4.91	2.62	0.49	1.53	0.40	14.65	72.87	0.21	1.00
11	2.40	4.85	2.71	0.48	1.58	0.41	14.41	72.92	0.23	1.00
12	2.19	5.12	2.79	0.43	1.59	0.39	14.41	72.93	0.17	1.00
13	2.29	5.04	2.63	0.47	1.61	0.35	14.35	72.99	0.24	1.01
14	2.49	5.03	2.68	0.49	1.63	0.38	14.20	73.00	0.09	1.01
15	2.24	4.99	2.67	0.51	1.54	0.35	14.39	73.12	0.20	1.01
16	2.45	5.07	2.51	0.47	1.63	0.47	14.11	73.13	0.15	1.02
17	2.59	4.76	2.73	0.45	1.58	0.50	14.01	73.19	0.18	1.01
ave.[2]	2.41	5.00	2.67	0.47	1.62	0.42	14.37	72.87	0.18	1.00
1σ	0.12	0.11	0.07	0.03	0.05	0.04	0.17	0.18	0.05	0.01

[1] NSF = normalization scaling factor

[2] Average of 17 analyses; average correlation coefficient of these values with Washington State University GeoAnalytical Laboratory database average for Mazama ash: 0.98

10.0-10.7 Road traverses through back-tilted slump blocks that are rotated down to the northwest. Arcuate closed depressions mark the lower edge of the slump blocks. Several closed depressions in the upper part of this area form marshy spots to the west of the road.

10.6 Lower complex of slump-overflow channels. The road is tangential with the well-defined lowest channel, which currently has several lodgepole pines growing in it (number 5 of lower complex, Fig. 21). The channel probably follows an arcuate slump depression. The head of the channel is choked with large boulders.

10.9 **STOP 15: Turnout, head of lower Soda Butte Valley.** Turnout on west at junction of faintly visible road, now closed, which lead to Trout Lake. A well-developed set of fluvial terraces is present from this area to the Lamar River confluence (Figs. 21, 22, 25). The turnout is on the T2 terrace; a walk down to the creek along the profile line of Figure 23 passes over the T3 terrace, the T4 terrace, and a broad area of high floodplain (fpu, Fig. 21) consisting of flood bars, channels, and eroded remnants of the T4 terrace supporting a grove of cottonwood trees. Tailings from the McLaren dam break were deposited within channels on the high floodplain formed during earlier, larger floods (e.g., 1918). The T4 terrace is also present on the opposite (SE) side of the creek below a high scarp in an f1 (mid-Holocene?) alluvial fan toe (Fig. 23).

Lower Soda Butte Creek Terrace Sequence

(Grant Meyer and James R. Anderson, Department of Geology, Middlebury College)

The terraces in Lower Soda Butte Creek were formed by incision within late Pinedale outwash. Figure 4a of Meyer et al. (1995) is a diagrammatic cross-section of the terrace sequence showing radiocarbon-dated units. Detailed total station surveys show that the terraces are paired, indicating discontinuous downcutting (Fig. 23). Where stratigraphic relations can be observed, the limited thickness of terrace sediments shows that these are fill-cut terraces (Bull, 1991). The terrace fluvial sediments overlying outwash gravels are no thicker than is expectable for the typical range of scour and fill by a vertically stable stream channel. Fill-cut terraces are formed by lateral migration of a vertically stable channel. The terrace sequence thus indicates a history of alternating lateral migration and vertical incision.

Surveyed long profiles show that terrace tread gradients are nearly constant and parallel over the length of the lower valley, but diverge slightly downstream (Anderson, 1995) (Fig. 24). Tread surfaces show consistent slopes; local deviations are abandoned channels, which are especially apparent on the T3b surface. The primary exception is at the head of the valley, where aggradation related to slump-sediment loading has raised the level of the channel for T3 and younger terraces. This effect extends downstream only 0.5-1 km downstream of the slump area for the T3 terrace. Below this point, the T3a and T3b terraces become distinguishable. Armoring by slump-derived boulders may have prevented further reduction of the channel gradient over this somewhat constricted reach. Recent (1918?) floods scoured channels through the T4 terrace, leaving remnant "scabs" of this surface (cf. Stop 16). Coarse gravels were deposited where flow diverges at the end of this reach, elevating the modern and channel floodplain.

Volcaniclastic bedrock near the footbridge had a limited effect on the terrace gradients (Figs. 22 and 24). The T0 and T1 terraces were not confined in this area and have consistent gradients. The T2 and younger terraces were confined within the bedrock slot at the footbridge, but gradients of the T3a and lower surfaces steepen only slightly through this area, if at all. Below the bedrock slot, terraces are poorly preserved. The effect of the Lamar River as a local base level for Soda Butte is not apparent further upstream, but may be significant in the last few kilometers (e.g., Leopold and Bull, 1979). Asynchronous downcutting of the two streams may have hindered terrace formation in the confluence area.

11.0 Road crosses the scarp between the T2 and T3 terrace treads.

11.3-11.4 **STOP 16: "Scabs" of T2 terrace.** Several island- or scab-like erosional remnants of the T2 terrace are present here, surrounded by the T3 surface (Figs. 21 and 22). Large linguoid flood bars lie on the T3 surface between these small "islands" of the T2 surface and the larger Station 62 remnant downvalley. High flood stages (from slump-dam overtopping?) may have breached the T2 surface here and continued down the NW valley margin. The broad anastomosing flow indicated by these features is typical of extreme floods (e.g., Baker, 1973).

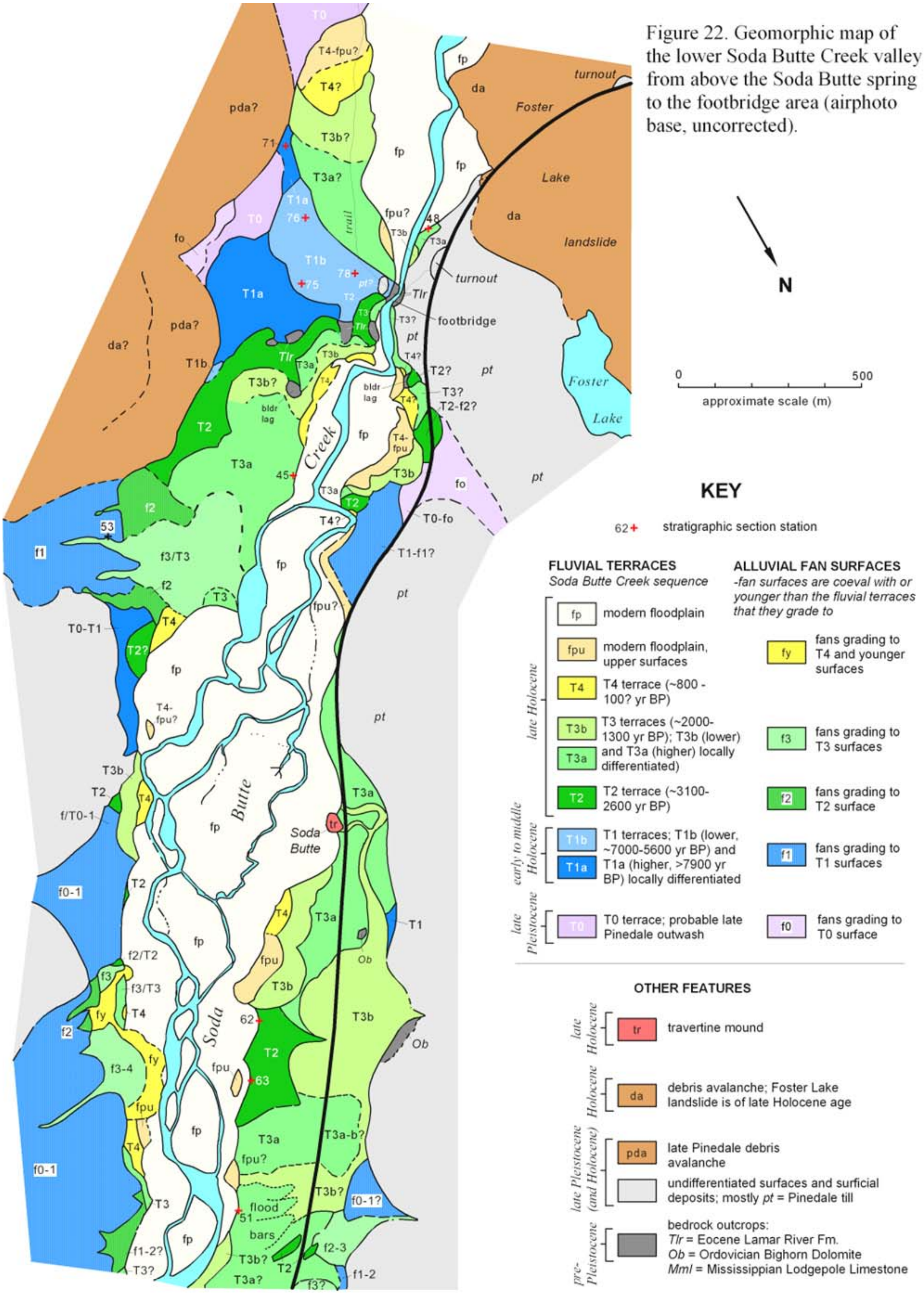


Figure 22. Geomorphic map of the lower Soda Butte Creek valley from above the Soda Butte spring to the footbridge area (airphoto base, uncorrected).

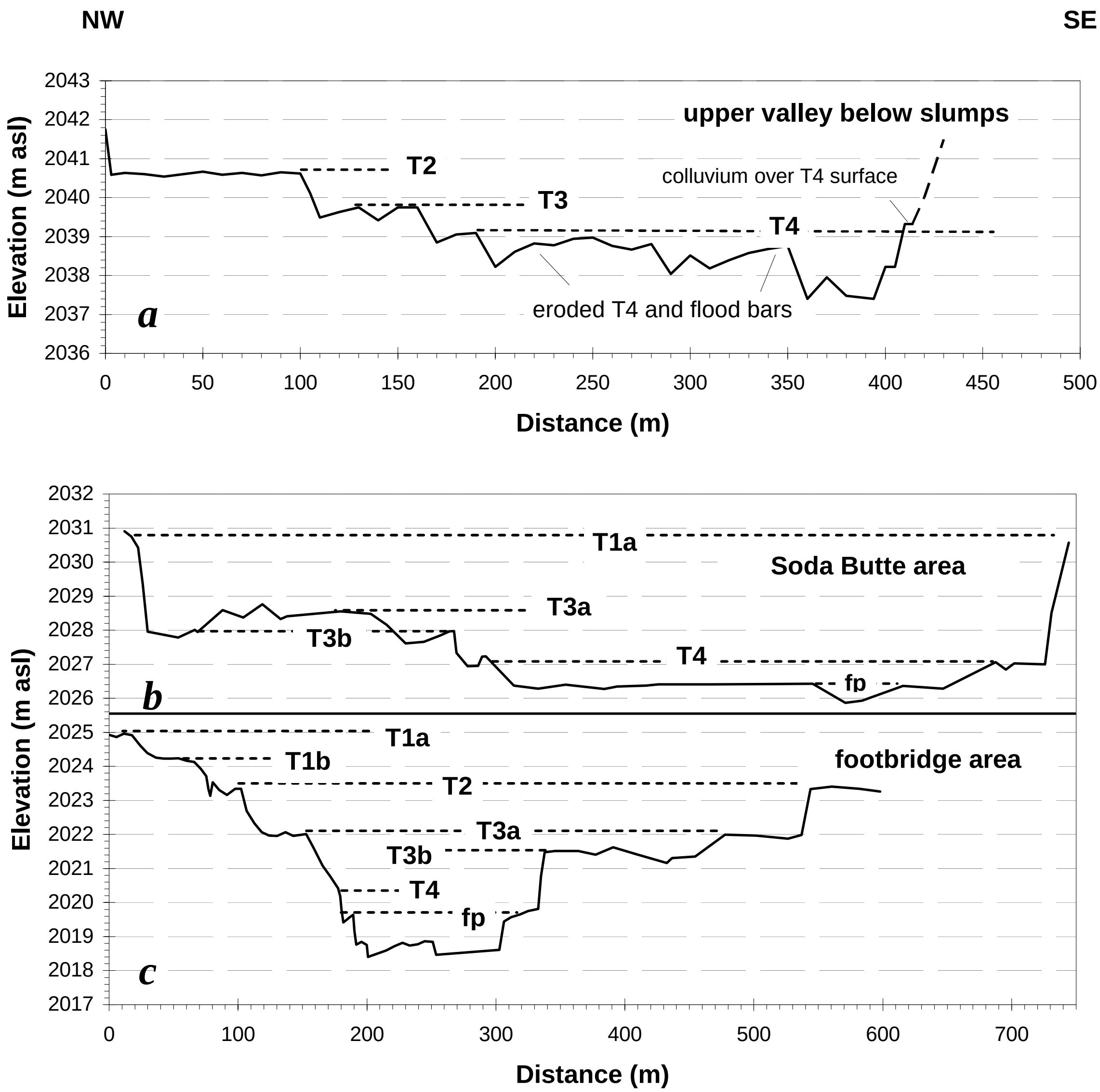


Figure 17. Cross profiles of terraces in the lower Soda Butte Creek valley, (***a***) in the upper valley below the slump area, (***b***) near the Soda Butte spring, and (***c***) ~300 m upstream from the footbridge, showing the paired nature of the terraces. Colluvium from the scarp above raises the level of the T4 terrace on the SE end of the upper valley profile (***a***). High gravel bars and eroded remnants of the T4 terrace are present on this profile, where flood flows (1918 flood?) diverge from the slump area constriction.

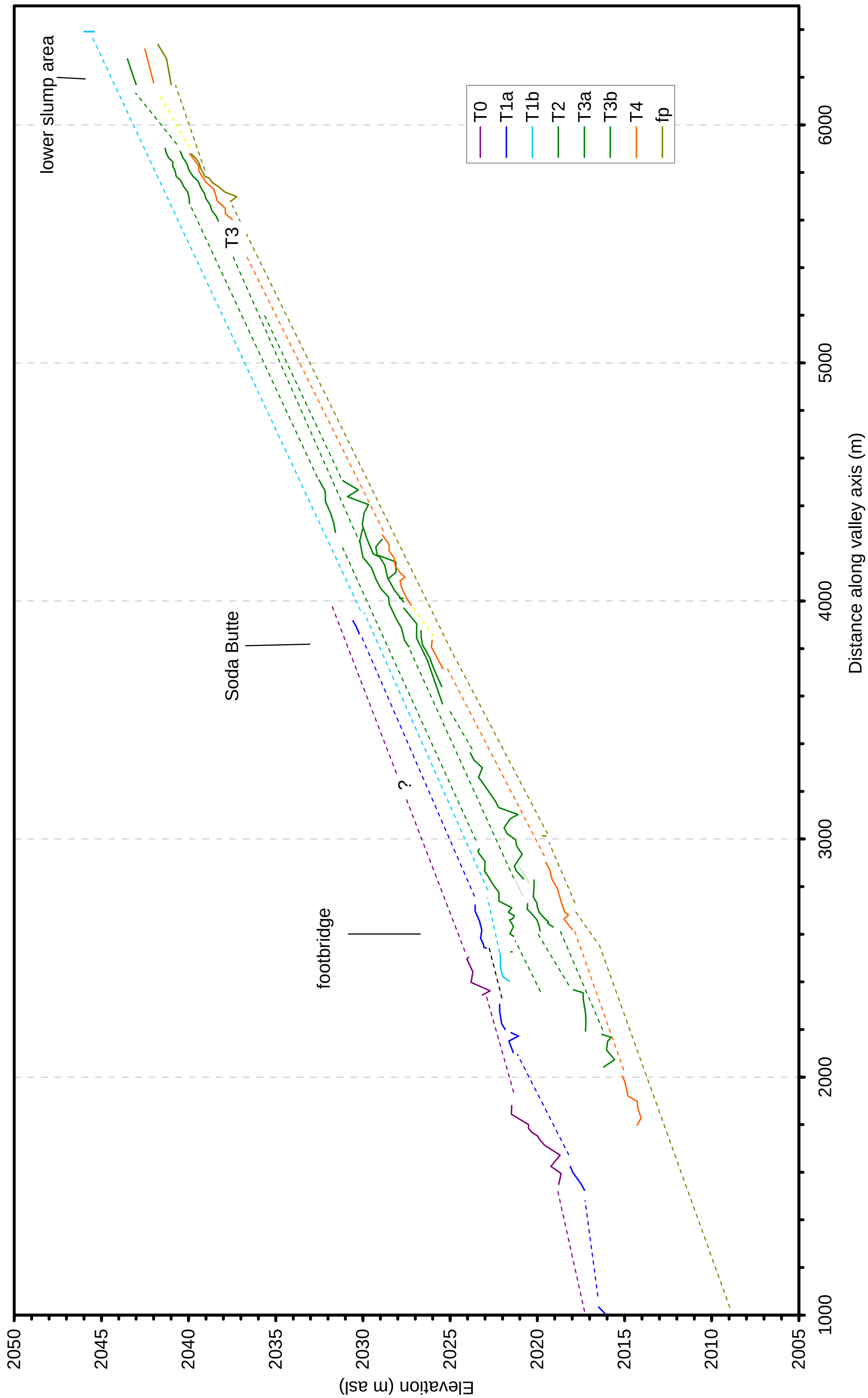


Figure 24. Long profiles of terrace treads of the lower Soda Butte Valley, with horizontal distance measured from the Lamar River confluence. Solid lines = profiles surveyed by total station; dashed lines = correlations. Possible elevation range of buried T1b terrace tread at upper end of valley (Station 44) shown by vertical bar.

11.5 Several well-developed secondary fans are visible across the valley, extending from higher distal fan surfaces of probable middle to early Holocene age (Figs. 21 and 22). In several places, these fans can be seen to grade to T2 and lower terrace levels.

11.7 Large island-like erosional remnant of the T2 terrace to the SE, with a narrow point projecting toward road. Sinuous meandering channels of the T3b terrace to the NW.

11.9 Island-like knob of Ordovician Bighorn Dolomite projecting above the T3a terrace. Behind this knob, a small remnant of the T1(a?) terrace is preserved at the valley margin.

12.0 **STOP 17: The Soda Butte.** The Soda Butte travertine mound was an early landmark named by 1870 prospectors (Haines, 1977). It is built on the T3a (or perhaps T2?) terrace surface. Fluvial gravels and finer (overbank?) sediments are mixed within the lowest travertine layers under the prominent ledge. The spring appears to be currently depositing travertine at a relatively slow rate on the scarp at the edge of the present floodplain. The mound suggests that rates of spring flow and travertine deposition were higher at the time of T3 terrace formation (and subsequently?), but no precise age range is known. U-series dating may be attempted in the future. Fluvial gravels under the T3a-T2 surface downstream of the Soda Butte are weakly cemented by hydrothermal fluids and may have been more resistant to erosion.

12.4 Looking across the valley floor, Station 45 lies along the prominent cutbank on the east side of Soda Butte Creek, at the edge of a broad area of the T3(a?) surface displaying a number of abandoned meanders (Fig. 22; Meyer et al., 1995, Figs. 5a and 6). It exposes well-laminated silty and fine sandy overbank sediments from 46-106 cm depth; detrital charcoal from a sandy cross-bedded layer at ca. 80-90 cm yielded an age of 1600 ± 80 yr BP. Imbricated channel gravel with faint lateral accretion surfaces forms the base of the section. The top of the section consists of bioturbated overbank sediments probably overlain by and mixed with a thin loess mantle. A low gradient fan has prograded over part of the T3 surface SE of the Station 45 cutbank. Farther SE, a higher, incised surface of this fan lies above a low stream-cut scarp and grades to the level of the T1 terraces. An age of 7420 ± 75 yr BP was obtained ~1.4 m below this surface at Station 53 on charcoal in a probable fire-related debris flow, indicating fan aggradation between the times of overbank deposition and floodplain widening on the T1a and T1b surfaces.

Terrace-Forming Processes in Lower Soda Butte Creek

The T3 terrace is notable for its breadth and meandering channel patterns. Estimates of sinuosity derived from abandoned T3 channels are 1.55 in the Station 45 area (Fig. 22; Meyer et al., 1995, Fig. 6) and 1.64 just upvalley of the Soda Butte, whereas the modern channel in these areas has a maximum sinuosity of about 1.28 and 1.29, respectively, using the maximum amplitude displayed in the present bar-and-island-braided system. T3 channels are narrower and deeper than the present channels of Soda Butte Creek. Overall, the thick overbank sediments and high-sinuosity, low width-depth ratio channels suggest that frequent moderate floods and a decrease in the ratio of bedload to suspended load characterized Soda Butte Creek during T3 formation (cf. Schumm, 1969). Similar high-sinuosity channel patterns are present on the T1a and T1b terraces as well, although they are more poorly preserved.

The geomorphology and sedimentology of lower Soda Butte terraces implies that increased average discharge promotes the active lateral migration of the channel and floodplain widening necessary for fill-cut terrace development. Formation of terrace treads is coincident with a low probability of fire-related sedimentation, suggesting cooler, effectively wetter conditions (Meyer et al., 1995, Figure 7). Available paleoclimatic information for the northern Yellowstone region is also consistent with interpretation of a generally wetter climate during terrace formation (Meyer et al., 1995, Figure 8). Greater runoff probably results mainly from deeper snowpacks and decreased evapotranspiration. Lateral erosion of fan toes in the middle and upper valley supplies ample sediment to the axial channel. Bedload gravels inhibit channel degradation, and high rates of suspended sediment transport allow overbank aggradation during frequent moderate floods. Sketches depicting climate-related fluctuations in alluvial fan and fluvial activity, including terrace development, are shown in Figure 26.

Details of the chronology of terrace formation are found in Meyer et al. (1995).

12.6 Excellent vantage point for viewing a nearly complete Soda Butte Creek terrace sequence to southeast: the T1a, T2, T3a, T3b, and T4 terraces are present, with low dark knobs of Eocene volcaniclastic rocks projecting above T1a surface.

12.9 **STOP 18: Soda Butte footbridge and trailhead turnout.** This stop is at the large turnout marked by the "Wildlife Exhibit" sign, which is also the head of the trail leading up the Lamar River. A footbridge lies across Soda Butte Creek where it flows through the narrow slot in Eocene volcaniclastic bedrock just below the parking area. The extensive surface directly across the creek is the T1b terrace, with low-relief steps up to the T1a and T0 terraces behind it; small knobs of volcaniclastic bedrock project above the terraces (Figs. 22, 25). Samples for dating the T1a and T1b terraces were obtained in abandoned channel depressions (Meyer et al., 1995). Late Holocene terraces are present on both sides of the footbridge. The T3b(?) terrace below the footbridge has high-relief transverse gravelly flood bars and little or no fine overbank cover. Two debris avalanche lobes border the opposite side of the valley (Figs. 22, 25). These deposits appear to be coeval with or slightly older than the T0 surface, although exact relations have not been determined. The upper part of the northeastern lobe is overlapped by a second, younger lobe. Below the turnout, the hummocky Foster Lake debris avalanche deposit projects onto low terraces and perhaps onto the modern floodplain level (see below).

T0 Terrace: Late-Pinedale Aggradation Surface

The T0 terrace is well preserved near the Lamar River-Soda Butte Creek confluence (Fig. 25). This fan-shaped aggradational surface was built by the Lamar River where it emerges from its confined upper valley about 3 km above the confluence. Using geomorphic position, sedimentology, and bar-and-swale surface morphology, Pierce (1974a) interpreted this highest terrace as an aggradational surface of latest Pinedale outwash. Axes of bars and swales indicate deposition by braided channels of the Lamar River.

At Station 68 (Fig. 6), a ca. 12 m-thick section of sediments underlying the T0 surface coarsens upward from well-stratified sand with shallow scour-and-fill structures and rip-up clasts of fine sediment, to poorly sorted, crudely stratified cobble and boulder gravel. The lower T0 sequence fines downvalley, and may be a deltaic deposit built into an ice-dammed lake in the Lamar Valley. This lake was probably impounded by a late-Pinedale ice lobe from the Slough Creek drainage (Junction Butte phase of Pierce, 1974b, 1979) (see Stop 20). Ice-damming occurred sometime between about 15,500 and 12,000 yr BP (Porter and others, 1983; Richmond, 1986; Sturchio and others, 1994). Fluctuating water levels in the lake may have produced the extensive oxidation stains observed in the lower T0 sequence. We infer that coarse sediments trapped above the lake were rapidly eroded after the ice dam was removed, causing aggradation of the upper T0 sequence at the head of the Lamar Valley. The sandy lower part of the sequence at Station 68 was recently observed to contain thin beds that are rich in rounded pebble-sized and finer pumice. The pumice is most likely reworked from previously deposited products of the Yellowstone caldera, as no rhyolitic volcanism younger than 70 ka has been documented in the region (e.g., Christiansen, 1984).

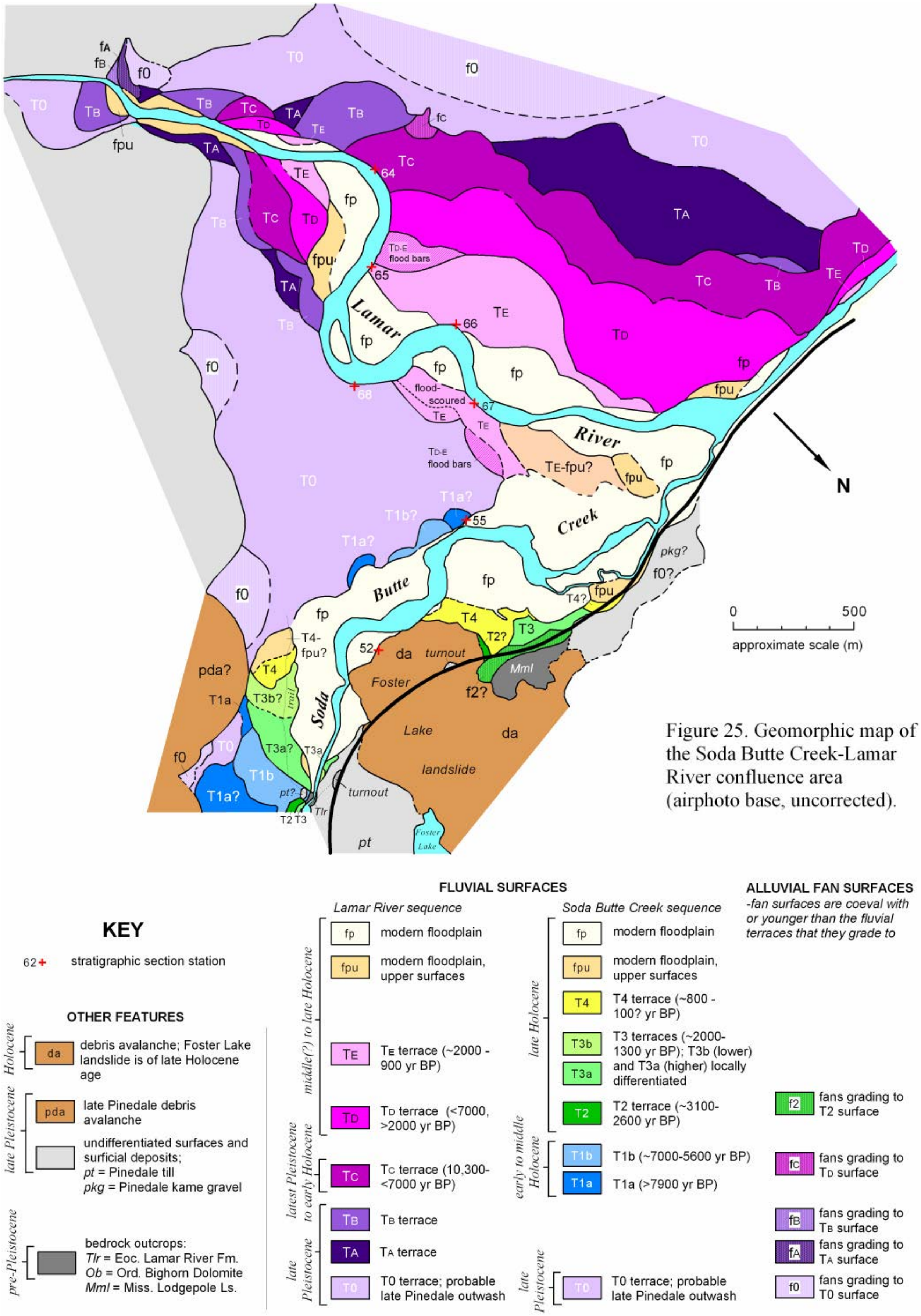


Figure 25. Geomorphic map of the Soda Butte Creek-Lamar River confluence area (airphoto base, uncorrected).

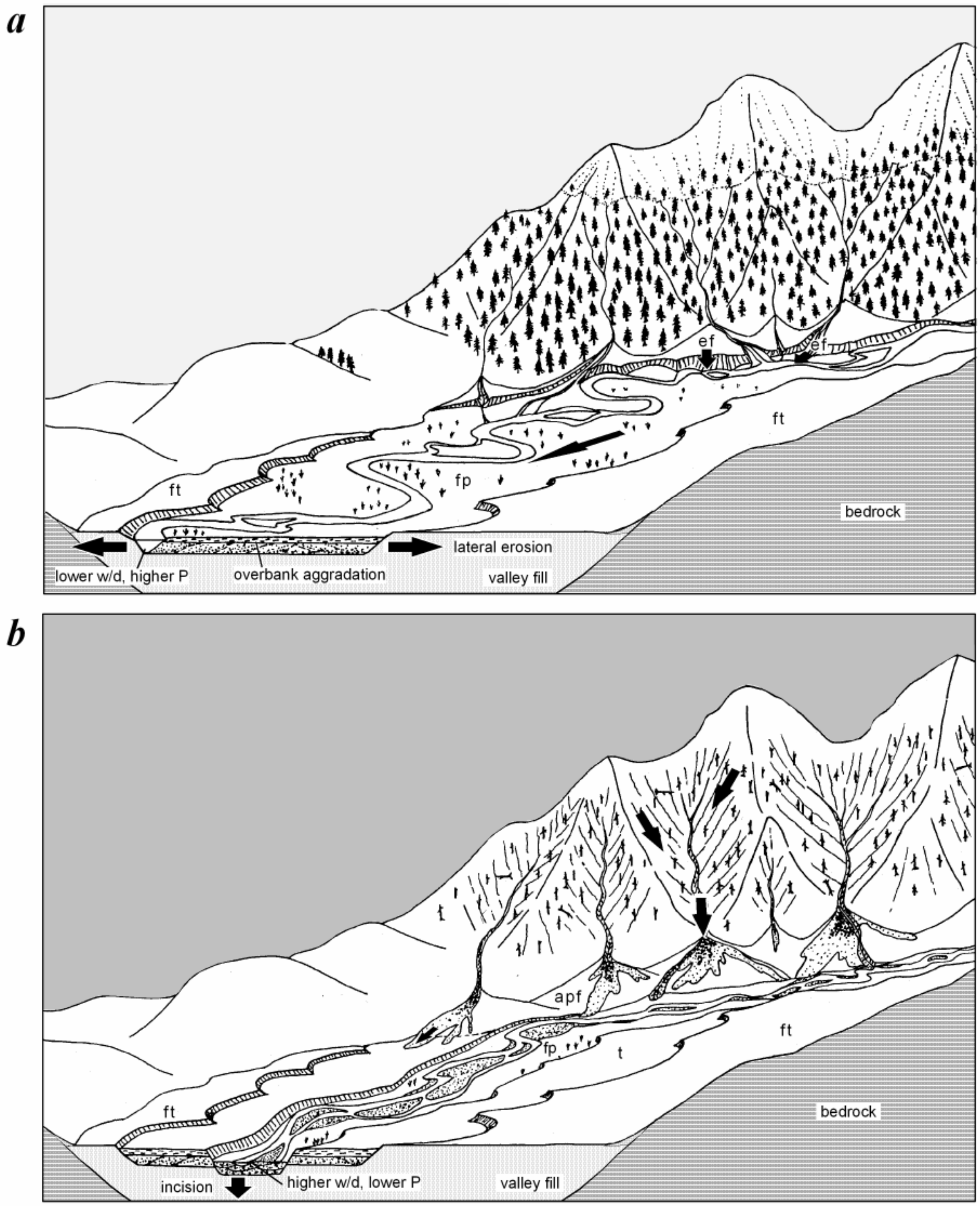


Figure 26. Sketches of idealized climate-related modes of Holocene alluvial activity in the Soda Butte Creek drainage, with arrows denoting dominant processes of sediment transport and geomorphic change; features are exaggerated for clarity. Note width/depth ratio (w/d) and sinuosity (P) changes of the axial fluvial channel. ***a,*** Activity during wetter periods, characterized by increased snowmelt runoff and frequent moderate floods. Increased average stream power promotes erosion of alluvial fan toes **(ef)** and lateral erosion, floodplain **(fp)** widening and overbank aggradation along the lower axial stream (Soda Butte Creek), where sideslope sediment input is low. The floodplain is inset within the latest Pleistocene outwash and deglacial valley fill, which stands as a fill terrace **(ft)** along the valley margin. ***b,*** Activity during drier periods, with recently burned slopes promoting debris flow transport to aggrading and prograding alluvial fans **(apf)**; stream power in upper Soda Butte Creek is insufficient to remove the fan sediment. The lower axial stream is incising (due to infrequent large floods?) within a narrowed floodplain **(fp)**, leaving the former floodplain of ***a*** as a fill-cut terrace **(t)**.

Although the T0 terrace is the oldest surface for which a soil was described in this study, soil development is rather weak. The T0 fill has no clasts of carbonate rock, as no carbonate strata are exposed in the Lamar River drainage above this point, and there is no significant carbonate accumulation in the soil. A weak color Bw is present in the fine cap (eolian and low-energy fluvial sediment?) on this surface. Very thin, milky-appearing coats on clast bases gravel in the gravel below are not effervescent and are probably silica (?). In contrast, a soil developed on limestone-bearing outwash gravel of similar age in the Slough Creek drainage has substantial carbonate accumulation with stage II morphology.

13.1-13.4 **Foster Lake landslide.** This clay-rich debris avalanche deposit is responsible for damming a side valley to form Foster Lake (Pierce, 1974a). Foster Lake contains significant organic-rich sediment, suggesting an age of several millennia, but Mazama ash is not present (C. Whitlock, personal communication, 1990). The landslide toe protrudes onto the present Soda Butte Creek floodplain, however, and diverts the modern channel, suggesting an age of only a few hundred years. Fluvial terrace gravels underlie the landslide deposit several meters above Soda Butte Creek in some areas (e.g., stratigraphic section 6 of Pierce, 1974a), but trenching of the landslide toe confirmed that this part of the deposit extends to the present floodplain level. Probably, like the Trout Lake landslide, the original debris-avalanche toe failed in a large, mobile slump or spread, as suggested by the steep scarp-like face north of the road.

13.3 Turnout/parking for horse trailers on south side. On the north side of the road, a marginal levee of the Foster Lake landslide is visible, where debris was diverted around the top of the cliff of Mississippian Lodgepole Limestone.

13.7-13.8 View across Soda Butte Creek floodplain of the T0 and T1 surfaces to the south. At Station 55 , the high cutbank near the west end of these surfaces, channel gravel associated with the T1a terrace contains carbonate rock clasts with provenance in the Soda Butte Creek drainage (Figs. 6, 25). Underlying Lamar River-derived gravel of the T0 fill lacks clasts of carbonate rock, as no carbonate strata are exposed in the Lamar River drainage above this point. The total thickness of T1a gravel and capping fines and loess at this measured section is 125 cm, and maximum thickness is about 2 m. An estimated mean value of bank height for the present lower Soda Butte Creek is between about 1.0 and 1.5 m. The thickness of the T1a deposits is thus well within the expectable scour depth (and deposit thickness) of about 1.75 to 2 times the bank height for a vertically stable stream system (Wolman and Leopold, 1957; Palmquist, 1975). This establishes the T1a as a fill-cut terrace (Bull, 1990).

13.6-14.3 The sloping bench above the road on the north is probably a kame, or perhaps an apron-like series of fans grading to the T0 surface.

14.3 **STOP 19: Soda Butte-Lamar River confluence.** Good view of Lamar River terrace sequence to south; the T0, T_A, T_C, and T_D terraces are prominent (in descending order) (Fig. 25). For those prepared to wade the river, this is a possible starting point for a hike upstream to view fluvial stratigraphy under the T1a and T1b (?) terraces at Station 55, and Lamar River stratigraphy at Stations 68 (T0 terrace), 64 (T_C terrace) and 65 (T_E terrace). Alternatively, a "dry-footed" hike may begin at the Soda Butte trailhead and footbridge (Stop 18) which crosses the broad expanse of the T0 surface to the above stations (Fig. 25).

Lamar River Terrace Sequence at the Head of Lamar Valley

A sequence of five inset terraces, designated T_A through T_E, was formed during incision of the Lamar River through the T0 fill at the head of the Lamar Valley. Figure 4b of Meyer et al. (1995) is a diagrammatic cross-section of the terrace sequence showing radiocarbon-dated units. The higher two terraces, the T_A and T_B surfaces, are of latest Pleistocene age. Station 64 is an excellent exposure of T_C terrace deposits (Figs. 6, 25). The base of channel gravels related to T_C activity is marked by a scour surface cut on well-stratified, iron oxide-stained pebble gravels (Meyer et al., 1995, Fig. 5b). The basal scour surface lies near the bankfull elevation of the Lamar River. Underlying gravels display horizontal bedding to low-angle scour-and-fill surfaces and a moderate to high degree of sorting. Although coarser, they are similar in depositional style and degree of oxidation to the lower sediments underlying the T0 surface, and are probably correlative gravels of latest Pinedale age. Overlying T_C sediments total 3-4 m in thickness, including a few to several tens of centimeters of partly eolian material. Given the bank height of ca. 2 m in pools of the present Lamar River, this deposit thickness is expectable for a vertically stable channel, thus the T_C terrace is a fill-cut surface.

Channel gravels comprise a (1) bouldery basal lag layer, and (2) pebble and cobble gravels displaying faint lateral accretion surfaces, the top of which defines a ca. 35 m wide channel. A crudely cross-stratified and contorted muddy drape deposit lies beneath the bouldery lag gravels, within a small trough in the basal scour surface. The upper part of this unit contains abundant coarse angular charcoal and may be a fire-related deposit. An age on the charcoal of 10,325 ± 100 yr BP (ca. 10,300 BC; Stuiver and Reimer, 1993) indicates that the Lamar River downcut rapidly from the T0 level ~15 m above the modern floodplain to only 3-4 m above it (Table 3). Formation of the T0 surface is thus approximately bracketed between ca. 14,000 and 11,000 yr BP (ca. 15,000-11,000 BC).

An age of 7205 ± 60 yr BP (ca. 6000 BC) was obtained within well-laminated overbank sediments 40 cm above T_C channel gravels at Station 64, indicating that the Lamar River was quasi-stable at the T_C level for at least 4000 calendar years. Accumulation of an additional 1.3 m of laminated overbank sediments above the dated level suggests that activity on the T_C terrace continued for at least several hundred years. The T_C terrace thus spans the time of T1a formation in Soda Butte Creek and extends to at least into early T1b time.

No detailed stratigraphic or chronologic data were obtained for the T_D terrace, in part because most of the thin overbank sequence on this surface is thoroughly bioturbated. The oxide-stained gravels which define the base of the T_C sediments (Fig. 5b, Meyer et al., 1995) also underlie the T_D surface and show it to be a fill-cut terrace. Exposures of T_E sediments were described at Stations 65, 66, and 67 (Figs. 6 and 25), but radiocarbon dates were obtained only from Station 65, the furthest upstream locality. At Station 65, a faintly stratified muddy sand filling a trough in channel gravels containing abundant coarse detrital charcoal yielded an age of 1940 ± 90 yr BP. This unit was bounded by an erosional upper contact, and was overlain by laminated overbank sediments with a discontinuous burned-in-place layer at 45 cm depth, dated at 920 ± 75 yr BP. These ages span the time of T3 overbank aggradation in Soda Butte Creek, and extend into the T3 to T4 downcutting interval. The surface morphology of terraces in the area of Station 65 suggests that this area has been the site of avulsion during large floods. A set of high bars on the west side of the T_E terrace (with crests intermediate in elevation between the T_D and T_E terraces) decline in height downstream and merge with the general T_E surface (Fig. 25).

Terrace formation is asynchronous between the Lamar River and lower Soda Butte Creek, but dated times of overbank aggradation are largely in correspondence between the two streams (Meyer et al., 1995, Fig. 7). This suggests that Holocene climatic fluctuations caused similar variations in discharge in each, but that greater resistance to downcutting resulted in fewer terraces along the Lamar (see Meyer et al., 1995 for discussion).

TABLE 3. INCISION RATES FOR SODA BUTTE CREEK (SODA BUTTE TO FOOTBRIDGE REACH), LAMAR RIVER ABOVE THE SODA BUTTE CONFLUENCE (STATION 64/65 AREA), AND MIDDLE SLOUGH CREEK (STATION 41/42 AREA) (SEE FIG. 1, MEYER ET AL., 1995 FOR LOCATIONS).

Terraces	**Time interval**	**ΔHeight** (m)	**Incision rate** (mm/yr)
Soda Butte Creek - rates between latest times of activity on terrace surface floodplains:			
T0-T1a[1]	11350-6600 BC	2.3	0.48
T1a-T1b	6600-4460 BC	1.0	0.47
T1b-T2	4460-790 BC	1.8	0.49
T2-T3	790 BC - 770 AD	0.6	0.38
T3-T4	770-1680 AD	0.9	0.99
T4-fp[2]	1680-1990 AD	1.4	4.52
Longer-term averages:			
T0-T2[1]	11350-790 BC	5.1	0.48
T2-T4	790 BC - 1680 AD	1.5	0.61
T0-T4	11350 BC - 1680 AD	6.6	0.51
T0-fp	11350 BC - 1990 AD	8.0	0.60
Soda Butte Creek - rates for incision episodes between terraces (latest dated time on upper terrace to earliest dated time on lower terrace):			
T1a-T1b	6600-5950 BC	1.0	1.54
T1b-T2	4460-1420 BC	1.8	0.59
T2-T3	790-94 BC	0.6	0.86
T3-T4	770-1205 AD	0.9	2.07
T4-fp	1680-1918 AD	1.4	5.88
Lamar River - rates between latest times of activity on terrace surfaces:			
T0-TC[1]	11350-4500 BC	10.5	1.53
TC-TE	4500 BC - 1200 AD	2.5	0.44
TE-fp	1200-1990 AD	2.0	2.53
Other averages:			
T0-TC channel[1,3]	11350-10240 BC	11	10.0
T0-TE[1]	11350 BC - 1200 AD	13.0	1.04
T0-fp	11350 BC - 1990 AD	15.0	1.12
Slough Creek - average incision rate over postglacial time:			
T0(?)[4] - fp	11350 BC - 1990 AD	3.5	0.26

[1] Assuming latest T0 activity ~11,000 yr BP and using ^{14}C calibration of Bard et al., 1993.

[2] fp = modern active floodplain.

[3] Rate between abandonment of T0 surface and incision to approximate bankfull level of TC channel at time of channel base date of 10,325 ± 100 yr BP (ca. 10,240 BC)(AA-7952).

[4] Latest Pinedale outwash terrace at Station 42, middle Slough Creek, assumed approximately equivalent in age to T0 surface near Lamar River-Soda Butte confluence.

17.0 **STOP 20: Lamar Ranger Station.** Osborne Russell, a rather literate man for a fur trapper, visited this area (which he called "Secluded Valley") in 1835. He later wrote:

> *There is something in the wild romantic scenery of this valley which I cannot . . . describe; but the impressions made upon my mind while gazing from a high eminence on the surrounding landscape one evening as the sun was gently gliding behind the western mountain and casting its gigantic shadows across the vale were such as time can never efface from my memory*.
>
> (O. Russell, in Aubrey Haines' 1955 edition of *Journal of a Trapper*)

Geomorphologists might suspect that Russell was deeply impressed by the beautiful forms of the alluvial fans extending from the foot of Specimen Ridge to the south, the "Fossil Forest" cliffs on the ridge face above, the broad fluvial terraces bordering the valley, and directly across the valley from this stop, the low bench near the mouth of Amethyst Creek underlain by the Osprey Basalt (Pierce, 1974a).

Lamar Valley ice-dammed lake *(Kenneth L. Pierce, U.S. Geological Survey)*. There appears to have been a glacial lake in the Lamar Valley, dammed by the recessional Slough Creek glacier. Fan/deltas built into the margin of the lake are suggested at (1) Rose Creek (site of the Lamar Ranger Station) which has a remarkably semicircular front at an altitude of about 6560 ft, and (2) the next fan upvalley, also with semicircular front at an altitude of about 6560 ft. Shoreline benches and fine-grained lake sediments, however, are hard to find. Along the Lamar River about 2.5-4 km upstream of the Lamar-Soda Butte confluence, an extensive sandy delta(?) fronts downvalley at an altitude of 6680 ft. The depth of the fill in the Lamar Valley between the Lamar-Soda Butte confluence and Lamar Canyon is unknown. The broad valley geometry, rarity of bedrock outcrops, and the possibility of glacial overdeepening suggests that there may be an unknown thickness of lake sediments beneath the alluvial fan and fluvial gravels in this reach of the Lamar Valley. Large Archean erratics scattered over Crystal Bench across the valley from Stop 20 are most likely derived from outcrops in the Lamar Canyon-lower Slough Creek area downvalley, because such erratics are much less common upvalley toward the Beartooth Plateau source area. Many of these large erratics rest on the surface and are not embedded in till, suggesting the possibility that they were ice-rafted and dropped into a Lamar Valley lake.

Mileage continuing to other major points on the Northeast Entrance Road:	
21.5	Slough Creek campground road junction.
26.5	Yellowstone River bridge
27.1	Tower Junction

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