



Geomorphology, sedimentology and stratigraphy of small, holocene, debris-flow-dominated alluvial fans, northwest Wyoming
by Mark Tod Cechovic

A thesis submitted in partial fulfillment of the requirements of the degree of Master of Science in Earth Sciences
Montana State University
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Abstract:

Modern examples of debris-flow-dominated alluvial fans used to construct fan facies models are based largely upon geomorphic studies of relatively few fans in the arid southwest U.S. The fan data base is biased from a spatial and climatic perspective and deficient in detailed documentation of internal fan sedimentology and stratigraphy. This study documents the geomorphology, sedimentology and stratigraphy of modern debris-flow-dominated fans in a 3 km² area in temperate, semi-arid, northwest Wyoming to increase the accuracy and diversity of fan facies models.

Ten small (< 0.22 km²), steep (11-14°), less than 33-m-thick, debris-flow-dominated fans formed at the base of small (<0.5 km²), steep (30-35°) catchments underlain by mudrock and sandstone. The area of some of the fans has been reduced and slope increased due to truncation of low gradient, distal areas by the Gardner River. Asymmetric cross-fan profiles are due to fan coalescence.

Fans are covered by a myriad of relict channels and matrix-supported, gravelly, debris-flow levee and lobe deposits. Some fans exhibit laminated sand and mud deposits produced by water or hyperconcentrated sheetflows. Fan channel avulsion is strongly controlled by channel-plugging debris flows. Previous channel avulsion points are marked by the spatial pattern of fan channels and debris-flow deposits.

Stratigraphic analysis of fan deposits reveals a preponderance of massive, ungraded, matrix-supported debris-flow deposits commonly scoured and overlain by fine-grained fluvial gravel and sand lenses. Mudrock-dominated fan drainage basins ensure abundant fine-sediment availability which favors formation of matrix-rich debris flows. Intervals up to 2 m thick consisting of sheetflow, mudflow and finegrained (mud to pebble) fluvial deposits also occur in the fan deposits. Due to abundant fine-sediment availability, sediment-laden water or hyperconcentrated sheetflows and/or mudflows occur frequently between large-scale, coarse-grained debris-flow events or result from fluid phases of matrix-rich debris flows.

The study-area fans exhibit some geomorphic, sedimentologic and stratigraphic characteristics which distinguish them from other modern fan examples reported in the literature. In contrast with many other debris-flow-dominated fans, study-area fans: 1) display slightly steeper longitudinal profiles, 2) contain mudflow and sheetflow deposits, and 3) lack sieve deposits.

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A thesis submitted in partial fulfillment
of the requirements of the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

December 1993

7378
C3241

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ACKNOWLEDGEMENTS

I thank Jim Schmitt, Steve Custer and Bill Locke for their advice and constructive criticism of this manuscript. I also thank Kristine, Bernie and John Cechovic for their assistance in fan and channel profile surveys in the field.

I am very grateful for financial assistance provided by the Montana State University Earth Science Department Graduate Research Teaching Assistantship, Donald L. Smith Memorial Scholarship and the Yellowstone Center for Mountain Environments.

Thanks go to the National Park Service for their cooperation and provision of accommodation at the Mammoth Campground in Yellowstone National Park.

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ABSTRACT

Modern examples of debris-flow-dominated alluvial fans used to construct fan facies models are based largely upon geomorphic studies of relatively few fans in the arid southwest U. S. The fan data base is biased from a spatial and climatic perspective and deficient in detailed documentation of internal fan sedimentology and stratigraphy. This study documents the geomorphology, sedimentology and stratigraphy of modern debris-flow-dominated fans in a 3 km² area in temperate, semi-arid, northwest Wyoming to increase the accuracy and diversity of fan facies models.

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Fans are covered by a myriad of relict channels and matrix-supported, gravelly, debris-flow levee and lobe deposits. Some fans exhibit laminated sand and mud deposits produced by water or hyperconcentrated sheetflows. Fan channel avulsion is strongly controlled by channel-plugging debris flows. Previous channel avulsion points are marked by the spatial pattern of fan channels and debris-flow deposits.

Stratigraphic analysis of fan deposits reveals a preponderance of massive, ungraded, matrix-supported debris-flow deposits commonly scoured and overlain by fine-grained fluvial gravel and sand lenses. Mudrock-dominated fan drainage basins ensure abundant fine-sediment availability which favors formation of matrix-rich debris flows. Intervals up to 2 m thick consisting of sheetflow, mudflow and fine-grained (mud to pebble) fluvial deposits also occur in the fan deposits. Due to abundant fine-sediment availability, sediment-laden water or hyperconcentrated sheetflows and/or mudflows occur frequently between large-scale, coarse-grained debris-flow events or result from fluid phases of matrix-rich debris flows.

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INTRODUCTION

Debris-flow-dominated alluvial fan facies models (e. g. Miall, 1978; Rust, 1978; Collinson, 1986) have been constructed using relatively few examples of modern, debris-flow-dominated alluvial fans in the arid, American southwest (e. g. Blissenbach, 1954; Beaty, 1963; Bull, 1964, 1972; Denny, 1965; Hooke, 1967). Conversely, facies models should be based on a large number of studies from diverse environments so that features common and unique to local examples can be discerned (Walker, 1984). Due to the restricted geographic setting of modern alluvial fan studies, an arid climatic bias may have been introduced into fan facies models because fans may be characteristic of the particular climate under which they formed (Nilsen, 1982).

Existing debris-flow fan facies models also suffer from a paucity of stratigraphic data. Much of the published research of modern alluvial fans which has provided the framework for fan facies models is based on geomorphic studies (e. g. Blissenbach, 1954; Beaty, 1963; Hooke, 1967; Bull, 1972). These studies do not include detailed vertical lithofacies profiles which document stratigraphic characteristics of fan deposits. Use of surficial evidence alone to determine fan depositional processes may yield an incomplete picture of fan

development because post-depositional reworking may obscure deposits left by the primary sediment transport processes responsible for fan construction (Blair, 1987).

Stratigraphic study of modern fans is difficult because natural, vertical exposures of fan sediment are rare and often restricted to entrenched channel walls in proximal-fan areas (Hooke, 1967; Nilsen, 1982). Investigation of fans with only proximal, vertical exposures may produce a spatially and volumetrically biased account of fan depositional processes and their deposits. Distal-fan sediment transport processes may be incompletely and/or incorrectly portrayed in published fan literature because interpretations of sediment transport processes have been based primarily on observations of distal-fan surface morphology without supporting stratigraphic evidence. By increasing knowledge of sediment transport processes which produce the stratigraphic, sedimentologic and morphologic characteristics of modern fans, the usefulness and accuracy of fan facies models will be improved.

The relative importance and distribution of debris-flow and water-laid deposits is highly variable between fans containing debris-flow deposits making formulation of a generalized facies model difficult. The generalized facies model for debris-flow-fans predicts that this type of fan will contain abundant debris-flow deposits and volumetrically less significant sheetflow/sheetflood, stream channel and sieve deposits (Hooke, 1967; Bull, 1972). The sediment transport

processes responsible for these deposits exhibit a continuous range of sediment to water ratios ranging from low-sediment-concentration water (stream) flow to high-sediment-concentration debris flow. Flows with sediment concentration intermediate between water flow and debris flow are termed hyperconcentrated (Beverage and Culbertson, 1964).

Though the spatial distribution of deposits on debris-flow fans is variable, previous work (e. g. Blissenbach, 1954; Beaty, 1963; Hooke, 1967; Bull, 1972) has helped establish a general pattern. Debris-flow deposits dominate proximal-fan areas, sheetflow/sheetflood deposits characterize distal-fan areas and stream-channel deposits occur in proximal- to distal-fan locations. Sieve deposits cluster around intersection points (e. g. Wasson, 1974) where a channel bed emerges onto the fan surface (Hooke, 1967).

Above an intersection point, the fan channel is confined and serves as the conduit for sediment which is deposited on lower portions of the fan. The point on an active fan where deposition takes place is the fan depocenter. Debris-flow fan depocenter shifts occur periodically and are attributed to fan channel blockage and avulsion by debris flows. However, this conclusion is drawn from relatively few studies of modern fans in California and Nevada (Eckis, 1928; Beaty, 1963; Hooke, 1967; Filipov, 1986; Whipple and Dunne, 1992). Because these field sites are from a restricted geographic and climatic setting, knowledge of channel avulsion mechanisms may be

incomplete and spatially biased.

Very little has been reported on the relationship between channel avulsion and spatial pattern of deposits on debris-flow fans. Maps showing the distribution of deposits on debris-flow-dominated fans (see Fig. 4 of Hooke, 1967, and Fig. 3 of Wells and Harvey, 1987) reveal diverse patterns which appear unpredictable. Pattern diversity has been attributed to depositional style variability and constantly shifting depocenter location over the surface of fans which produces random interbedding of sheetflow/sheetflood, stream-channel, sieve and debris-flow deposits (Collinson, 1986).

The debris-flow fan facies model is still evolving. A comprehensive, geomorphic study by Hooke (1967) of the debris-flow-dominated Trollheim fan in east-central California, provided the basis for "widely held, fundamental alluvial fan facies concepts..." (Blair and McPherson, 1992, p. 762). Hooke (1967) termed lobate-shaped deposits of open-framework gravel sieve deposits. Since then, sieve deposits have been portrayed as common features of fans with abundant debris-flow deposits (Miall, 1978; Collinson, 1986). Recent geomorphic, sedimentologic and stratigraphic re-evaluation of the Trollheim fan by Blair and McPherson (1992) showed that sieve deposits were actually debris-flow deposits whose tops had undergone surface winnowing by runoff or possibly wind; matrix was found at shallow depths. This discovery emphasizes the need for more studies of modern debris-flow fans which include

geomorphic, sedimentologic and stratigraphic data.

The purpose of this research is to increase the usefulness, accuracy and diversity of debris-flow fan facies models by documenting the geomorphology, sedimentology and stratigraphy of modern debris-flow-dominated alluvial fans in an approximately 3 km² area in temperate, semi-arid, northern Yellowstone National Park, northwest Wyoming (Fig. 1). The geomorphic, sedimentologic and stratigraphic attributes of the fans can be used to determine the sediment transport processes involved in fan construction and mechanisms of channel avulsion which produce depocenter shifts on the fans.

Debris-flow-dominated fans forming at the base of the west flank of Mt. Everts (Figs. 2-4) represent an excellent opportunity for geomorphic, sedimentologic and stratigraphic study. Detailed morphologic investigation of fan surfaces is possible because an abundance of well-preserved channels and debris-flow lobes and levees are present on the sparsely vegetated fans. Sediment transport events occurred during and immediately prior to this study presenting an opportunity to compare the recent, fresh morphologic and sedimentologic characteristics of deposits with older deposits. The study-area fans display natural, vertical exposures of fan sediment at proximal-, medial- and distal-fan locations which can be used to document fan deposit sedimentology and stratigraphy. Vertical exposures of distal-fan deposits are available due to fan toe truncation by the Gardner River.

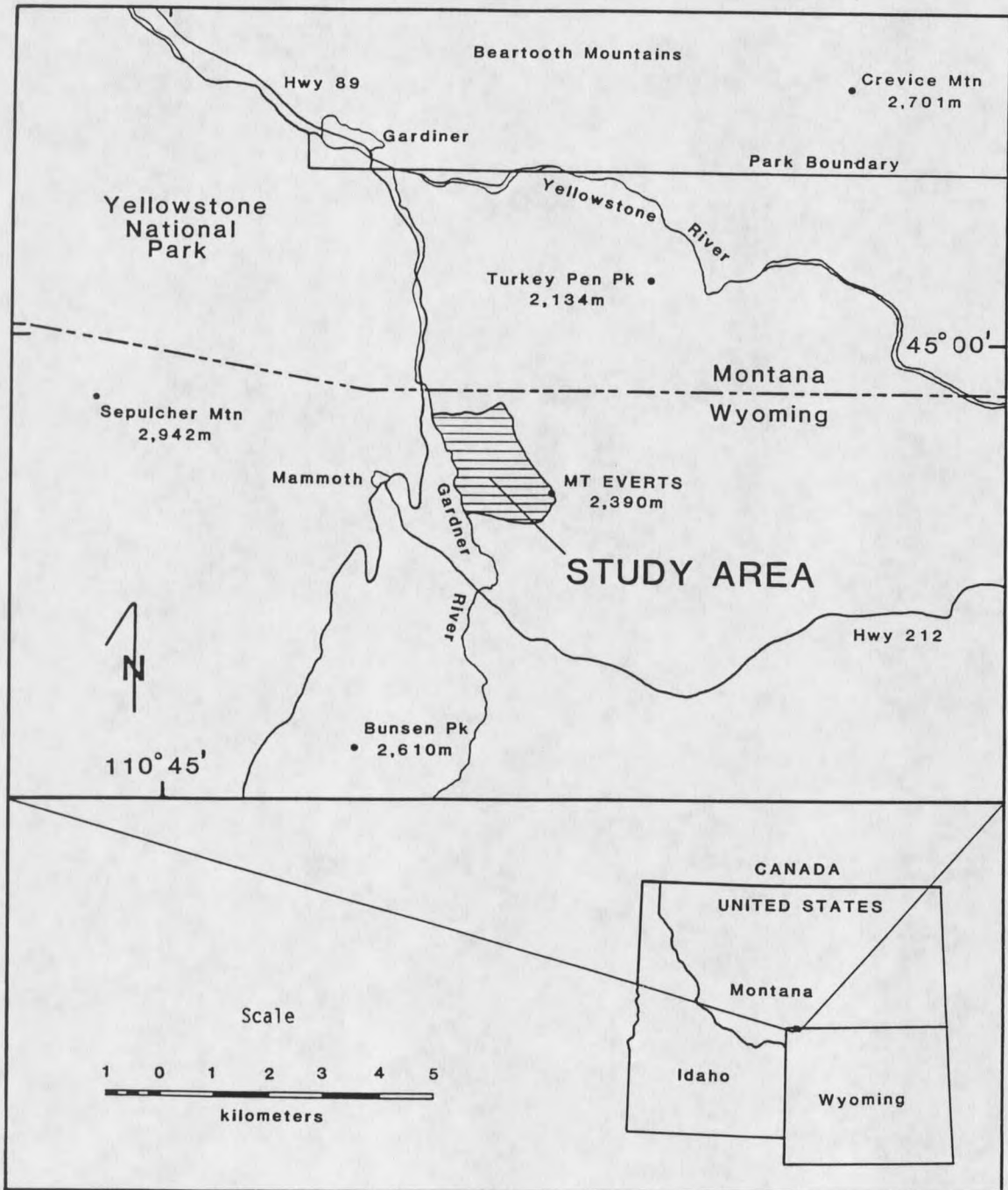


Figure 1. Map showing location of study area in the Gardner River valley along the west flank of Mt. Everts. The 1: 100,000 scale, 1986 Absaroka Beartooth Wilderness map produced by the U. S. D. A. Forest Service was used as a map base.

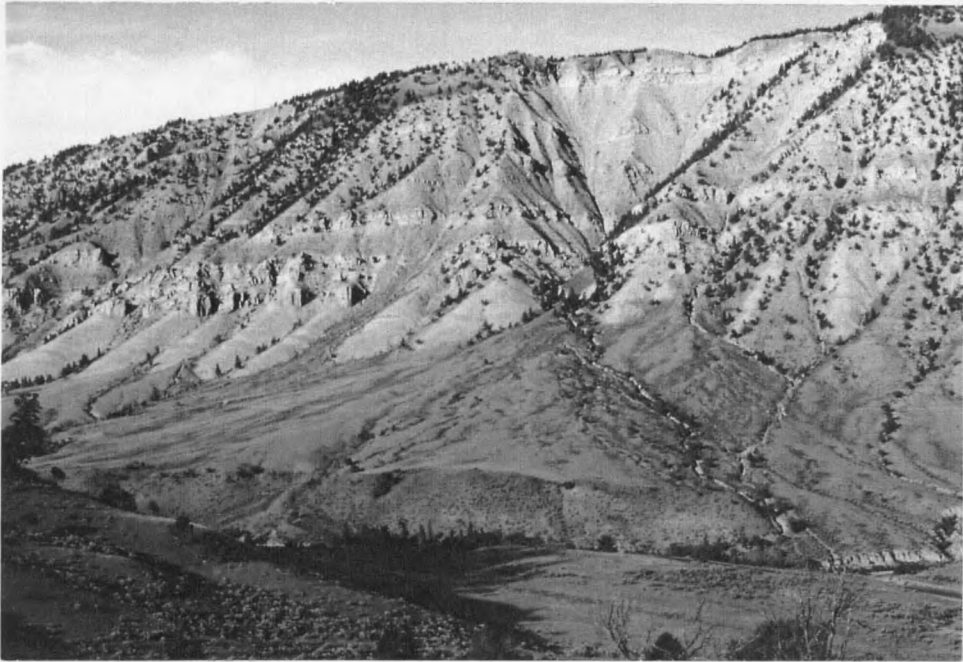


Figure 2. Northern third of study area showing debris-flow-dominated fans at the base of Mt. Everts. Left edge of large fan in center of photo is the northern study area boundary. View is to the east. Gardner River is in foreground.



Figure 3. Central third of study area showing coalescing fans at the base of Mt. Everts. View is to the east. Gardner River is in foreground.



Figure 4. Southern third of study area showing small fans at the base of Mt. Everts. The southernmost fan formed on the toe of a large landslide deposit (right-central portion of photo). Gardner River can be seen in foreground. View is to the east.

PREVIOUS RELATED WORK IN STUDY AREA

Earlier observations and stratigraphic analysis of one of the alluvial fans in the study area (Craig, 1986; Schmitt and others, 1989) indicated that debris-flow events played an important role in fan construction. However, before the comprehensive study presented here, no one has documented overall fan morphology or fan-surface deposit morphology and sedimentology.

METHODS

Black and white, 1:40,000-scale, 1989 U. S. National Aerial Photography Program (NAPP) vertical photographs were enlarged to a scale of approximately 1:5,460 and used as a base for all maps presented in this report except the study-area location map (see Fig. 1 caption). Because the photographs are not orthophotographs, some photo distortion is reproduced in the maps. Comparison between the enlarged photographs (1:5,460 scale) and a 1:24,000-scale, 1986 United States Geological Survey topographic map of the Mammoth Quadrangle revealed a scale error of less than +3% in the low-relief area occupied by alluvial fans on the photo. Photo scale error may approach +44% on the steep west-facing flank of Mt. Everts above the fan apexes due to extreme relief (there is 350 to 400 m vertical elevation decrease over about 600 m horizontal distance from the crest of Mt. Everts to the fan apexes).

A geologic map was constructed to characterize the rock types and structural setting of the fan environment, and a geomorphic map was constructed to characterize the type, scale, form and distribution of the fan-surface deposits. Published, stratigraphic sections measured in and adjacent to the study area (Fraser and others, 1969) were used as a field

aid to map contacts between rock formations shown on the geologic map; strike and dip were measured in the field. Qualitative observation of morphologic and sedimentologic characteristics provided the basis for differentiation of surficial deposits delineated on the geomorphic map. All mapping was done in the field and no feature was mapped without a field check.

Because of the large photo scale error (up to +44%) on the 1:5,460-scale, NAPP vertical aerial photograph in the area of the fan drainage basins, a 1:24,000-scale, 1986 United States Geological Survey topographic map of the Mammoth Quadrangle was used to determine fan drainage basin slope and area. Very little photo scale error (< +3%) occurs in the area occupied by the alluvial fans in the study area, so fan area was estimated from the black and white, 1:5,460-scale, NAPP vertical aerial photographs.

Longitudinal and cross-fan profiles of two alluvial fans were surveyed using a tripod-mounted auto level, 25-ft telescoping surveyor's rod and 300 ft cloth tape. Vertical elevation change to the nearest 0.01 ft was recorded at 30-ft slope intervals. All English measurements were converted to metric at the end of the field season.

To show the distribution and scale of channel plugs which are important to channel avulsion, a longitudinal profile was constructed along an active fan channel from its junction with the Gardner River up to the fan apex. The longitudinal

profile was made with a 100 m cloth tape and hand held clinometer by recording slope distances to the nearest 0.10 m every 1.77 m (eye level) of vertical elevation increase. The exact location of all abrupt channel bed elevation changes of 2 m or more were recorded.

Sediments were categorized into lithofacies based on qualitative field descriptions of unit geometry and contacts, clast and matrix lithology, sedimentary structures, organic matter, clast and matrix grain size, shape, angularity, sorting and fabric at ten field sites exhibiting near vertical exposure of alluvial fan deposits. Sediments with similar physical characteristics that are objectively observed or measured can be grouped into lithofacies (Reading, 1986) which provide a framework for interpretation of sediment transport processes. Facies codes used in this report are based on Miall's (1978) classification scheme. The three general sediment size classes noted include: 1) gravel (> 2 mm), 2) sand (0.06 mm to 2 mm), and 3) mud (< 0.06 mm). Grain sizes corresponding to very fine, fine, medium, coarse and very coarse sand, and granule, pebble, cobble and boulder gravel are from Ehlers and Blatt (1982, Table 13-1). In this study, matrix was defined as all sediment finer than 2 mm (sand and mud); clasts were defined as all particles larger than 2 mm (gravel). Estimates of sorting and degree of particle rounding were based on published charts (Ehlers and Blatt, 1982, Figs. 13-2 and 13-4, respectively).

ALLUVIAL FAN SEDIMENT TRANSPORT PROCESS AND DEPOSIT TERMINOLOGY

Flow characteristics control the sedimentologic and geomorphic attributes of the deposits. These attributes can be used to differentiate between deposits formed from confined and unconfined water flows, hyperconcentrated flows and debris flows (Costa, 1988). Definition of these flow types is necessary because of inconsistent usage in the literature (see discussions in Hogg, 1982, and Pierson and Costa, 1987).

Water Flow

Water flow is a turbulent mixture of sediment and water moving in two separate phases. Fine sediment is transported in suspension and coarser sediment is transported by saltation and rolling along the channel bed (bed load). Water flow typically has sediment concentrations between 1 and 40% by weight (Costa, 1984). Pure water exhibits negligible shear strength and will flow in infinitely thin sheets in response to any applied shear stress.

An unconfined (unchannelized), sheet-like mass of flowing water can be termed either a sheetflow or sheetflood depending on the magnitude and frequency of the event, though a

continuum between these two types exists in nature. Sheetfloods typically originate on steep slopes ($> 11^{\circ}$) and are high-magnitude, low-frequency events characterized by turbulent sheets of floodwater up to several feet deep moving at velocities up to 10 m per second (Hogg, 1982). Sheetflows are restricted to gentle slopes ($< 3^{\circ}$) and are low-magnitude, high-frequency events which exhibit mainly laminar flow, are millimeters to several centimeters deep and move at centimeter per second velocities (Hogg, 1982).

Deposit Morphology and Sedimentology

Deposition from water flow produces bars, sheets, fans and splays with little topographic expression because of the minimal shear strength possessed by water (Costa, 1988). Particle transport mechanisms result in gravelly deposits which are poorly to well sorted, clast-supported with a sandy matrix and commonly exhibit clast imbrication (Smith, 1986). Both coarse- and fine-grained deposits commonly display horizontal or inclined stratification and cut and fill structures resulting from scour under turbulent flow conditions (Harms and others, 1982).

Channelized water flows of moderately large discharge are invoked by Hooke (1967) to explain the formation of sieve deposits which are 10 to 30 ft-high, matrix-free, pebble to boulder gravel lobes. Sieve deposits may form if a channelized, gravel-charged water flow: 1) experiences near

instantaneous drainage into a porous and permeable fan surface which causes gravel deposition, or 2) encounters a sudden decrease in channel slope which causes deposition of gravel while the rest of the water flow moves through the gravel lobe and continues downslope (Hooke, 1967).

Hyperconcentrated Flow

Hyperconcentrated flow, like water flow, contains sediment and water in separate phases; sediment transport is in suspension and on the bed. Sediment concentration of hyperconcentrated flows is between 40 and 70% by weight (Beverage and Culbertson, 1964). The increased fluid density of hyperconcentrated flows allows bedload movement of larger particles than water flow at similar flow velocities. As turbulence becomes dampened at high sediment concentrations, buoyancy and grain interactions aid in keeping particles in suspension (Costa, 1984). Hyperconcentrated flows possess relatively little shear strength and flows will spread into thin sheets. Thus, like water flows, unconfined (unchannelized) hyperconcentrated flows can be classified into sheetflows or sheetfloods.

Deposit Morphology and Sedimentology

Landforms resulting from hyperconcentrated flow are similar to those produced by water flows and are often

difficult to distinguish from water-flow deposits (Costa, 1988). Hyperconcentrated-flow deposits may show weak horizontal stratification but do not show inclined stratification and are frequently normally graded (Smith, 1986; Costa, 1988). Gravelly deposits resulting from hyperconcentrated flows typically show weak imbrication, are poorly sorted and clast-supported with a poorly sorted matrix (Smith, 1986; Costa, 1988).

Debris Flow

Debris flows are characterized by laminar shear. Sediment and water move together as a single phase in a visco-plastic mass possessing considerable shear strength (Johnson, 1970). Shear strength is imparted by clay and silt which produce cohesive strength (Middleton and Southard, 1978), and internal friction from particle interlocking in clast-rich, poorly sorted flows (Rodine and Johnson, 1976). Sediment concentration is 70 to 90% by weight and particles are transported by rolling, cohesive strength, buoyancy and grain interactions (Costa, 1988). Turbulence is minimal and is restricted to more water-rich, sediment-poor phases of a debris-flow event. A pseudoplastic or fluid debris flow possesses a lower fine-sediment to water ratio than a visco-plastic debris flow which results in lower shear strength and possibly some turbulence during flowage (Shultz, 1984). A

mudflow is a type of debris flow which contains predominantly sand and finer sediment (Bull, 1972).

Deposit Morphology and Sedimentology

Debris flows create gravelly lobes and U-shaped channels bounded by gravelly levees. The high shear strength of debris flows causes sharp topographic breaks at levee and lobe margins giving them a distinct, diagnostic appearance (Costa, 1984). Deposits are matrix- to clast-supported, poorly to extremely poorly sorted, lack stratification, display variable clast orientation and are massive, ungraded, inversely graded or normally graded (Hooke, 1967; Bull, 1972; Nilsen, 1982; Costa, 1984, 1988). Fluidal or pseudoplastic debris flows create deposits that tend to be massive, ungraded to normally graded and clast-supported (Nemec and Steel, 1984; Shultz, 1984).

ALLUVIAL FAN ENVIRONMENT

To characterize the study-area alluvial fan environment, topographic, climatic, hydrologic, vegetal, geologic and fan drainage basin characteristics are presented. The fan environment controls the style of sediment transport processes involved in fan construction (Hooke, 1968; Bull, 1977; Harvey, 1992). The dominant sediment transport process which has built a fan is the primary factor responsible for differences in fan morphology and facies which exist between fans (Kochel and Johnson, 1984).

Topography

The eastern edge of the study site is the crest of Mt. Everts which serves as the eastern drainage divide for fan drainage basins. Mt. Everts is a massive, north-south-trending ridge which maintains a crest elevation of over 2,250 meters above sea level (m.a.s.l.) for about 3.5 km. Fan apexes occur immediately below fan drainage basins at about 1,900 m.a.s.l. Fans have prograded westward to the Gardner River where most of them have been truncated by the river. Topographic relief between the crest of Mt. Everts and the Gardner River is about 590 m over a horizontal distance of

approximately 1.5 km.

Climate

The study site is in a temperate, semi-arid climatic region characterized by extreme seasonal temperature ranges and episodic precipitation and snowmelt events. Climate information for the study area is based on 45 years of record from a weather station located about 1.5 km to the southwest of the study area at Mammoth, Wyoming. Northern Yellowstone Park experiences temperature extremes which range from a mean daily minimum in January of -12.3°C to a mean daily maximum in July of $+27.0^{\circ}\text{C}$ (Craig, 1986). Average annual precipitation is 39.47 cm, ranging from a record minimum of 28.14 cm to a record maximum of 51.51 cm with an average snowfall of 193.24 cm (Climate Data, CD ROM, 1992). Most often, rains are localized, brief, intense showers during spring and summer (Craig, 1986). However, periods of moderate rainfall lasting 1 to 2 days are not uncommon. Several such storms occurred at the study site during the Summer of 1992 resulting in debris-flow and sheetflow depositional events on many of the alluvial fans. During early spring, the area commonly experiences locally heavy, wet snowfall events followed by warm temperatures and rapid melting which may trigger episodic sediment transport events. Periods of rapid, intense snow melt may also occur during winter or spring as a result of

warm, dry, gusty chinook winds.

Hydrology

Near the top of three fan drainage basins in the study area are groundwater discharge zones which sustained continuous flow during this study (June through October, 1992). Small streams resulting from the groundwater discharge zones occupy channels (Fig. 5) incised to varying depths which lead from fan apexes to the Gardner River and serve as a conduit for sediment deposited on the alluvial fans. The north-flowing Gardner River has an average annual discharge of



Figure 5. Incised, active, fan channel on distal portion of fan C (see Fig. 7 for location) with small, spring-fed stream. Rock hammer on upper right bank for scale.

6.2 m³/second (Shields and others, 1986) and 0.015 gradient along the western boundary of the study area.

Vegetation

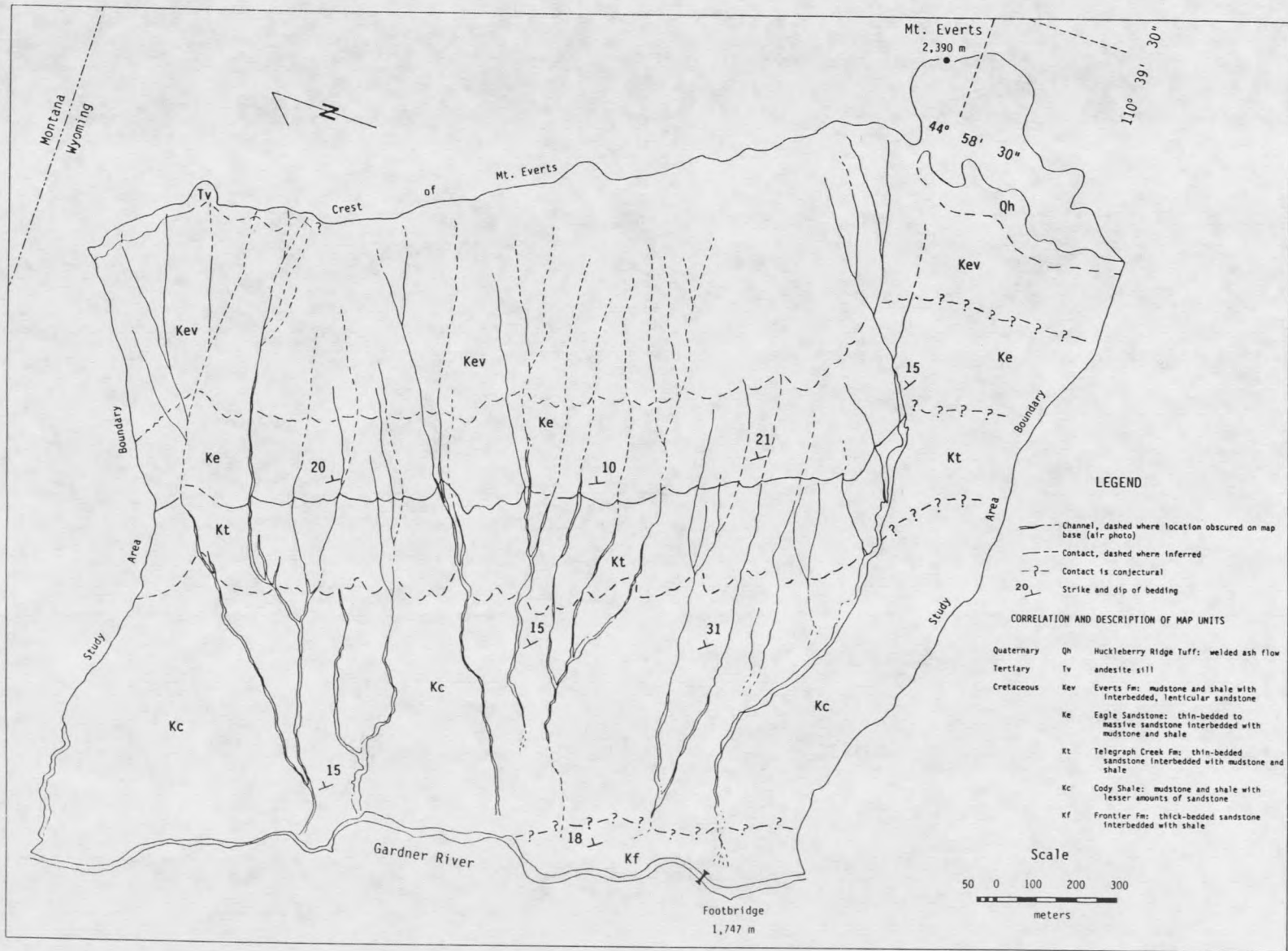
Pine, fir and juniper trees line active channel edges on the alluvial fan surfaces and also grow on the west face of Mt. Everts between rapidly eroding fan drainage basins. Fan drainage basins are very sparsely vegetated. Sagebrush, rabbitbrush, grasses and small cactus cover the alluvial fan surfaces and to a lesser extent the rocky west face of Mt. Everts. Grasses, small shrubs and occasionally cottonwood trees grow adjacent to the Gardner River.

Geology

Bedrock

The study area contains a complete section of mudrock and sandstone from the Middle Cretaceous Frontier (Kf) through Upper Cretaceous Everts Formations (Kev) which strike northwest and dip from 10 to 30° to the northeast (Fig. 6).

Figure 6. Geologic map of study area showing a complete stratigraphic section of rocks from the Middle Cretaceous Frontier through Upper Cretaceous Everts Formations. Distances in the Everts (Kev) and Eagle (Ke) Formations may be distorted by as much as +44%; see METHODS section for explanation.



Twenty-four joint measurements (not shown in Fig. 6) were taken in a north-south transect across the study area and in outcrops between Highway 89 and the Gardner River opposite the study area. The Mt. Everts area is pervaded by two sets of steeply dipping joints. One joint set strikes north-south and dips from 64° east to 52° west and the other strikes east-west and dips from 77° south to 56° north.

The upper Frontier Formation (Kf) forms sandstone bluffs along the west side of the Gardner River and is correlated to an isolated, sandstone-cored knob (18° bedding dip) in the southwest portion of the study area (Fig. 6). The Cody Shale (Kc) and Telegraph Creek Formations (Kt) are covered by meter-scale thicknesses of fan, colluvial and glacial deposits in valleys between east-west trending ridges. The east-west trending ridges cored by the Cody Shale (Kc) and Telegraph Creek Formations (Kt) are covered by thin (centimeters to probably < 1 m) colluvial and sometimes glacial deposits. The contact between the Cody Shale and Telegraph Creek Formation is conspicuous because of an upslope change in soil color from gray to yellow due to an increasing abundance of sandstone and decreasing amount of mudrock in the Telegraph Creek Formation (Fraser and others, 1969). The Eagle Sandstone (Ke) forms cliffs of thin-bedded to massive sandstone separated by mudrock units. Narrow canyons and sandstone bluffs of the Eagle Sandstone mark the bottom of the precipitous west face of Mt. Everts (Fig. 6). Above the Eagle Sandstone, fan

catchments have been carved into the Everts Formation (Kev) which is composed predominantly of highly erodible mudrock (Fig. 6). The Everts Formation is generally exposed, but may be locally covered by scree.

A mafic andesite sill (Tv) of probable Eocene age (Fraser and others, 1969) intrudes the Everts Formation and forms a resistant caprock above the large catchment which supplies sediment to the northernmost fan in the study area (Fig. 6). The Huckleberry Ridge Tuff (Qh), also called the Yellowstone Tuff, is a welded ashflow erupted from the Yellowstone Caldera during the Pleistocene (Fraser and others, 1969), and now forms a vertical cliff which caps the crest of Mt. Everts south of the summit (Fig. 6).

Surficial Deposits

Plate 1 is a geomorphic map of the study site which illustrates the spatial distribution of fan deposits, bedrock, colluvium, Pinedale-age glacial till and catastrophic flood deposits (Pierce, 1973), landslide and Gardner River fluvial deposits. Detailed mapping of fan surfaces shows that they are dominated by debris-flow levee and lobe deposits with a lesser amount of sheetflow deposits (Plate 1). The distribution and significance of these deposits will be discussed later.

Outcrops of bedrock (B), locally covered by colluvium (C) and glacial till (Gt), dominate the eastern half of the study

area (Plate 1). The western or topographically lower third of the bedrock-dominated area is composed of cliff-forming, resistant sandstone of the Eagle Sandstone (compare Fig. 6 and Plate 1). Mudrock and thin sandstone of the Everts Formation, sometimes covered by a thin layer of scree, occupy fan catchments in the eastern or topographically upper two thirds of the bedrock-dominated area (compare Fig. 6 and Plate 1).

Below the bedrock-dominated area, colluvium (centimeters to probably < 1 m thick) and glacial till cover ridges between fan deposits (Plate 1). Glacial till is easily differentiated from fan deposits by the presence of boulders of basalt, limestone and granite in the glacial till. These rock types are not indigenous to the study area and occur in abundance only in glacial and Gardiner River channel and terrace gravel. Catastrophic proglacial flood deposits (Gf) which form high, coarse-gravel ridges near the Gardner River in the northwest part of the study area (Plate 1) are correlated with deposits mapped previously at a 1:62,500 scale by Pierce (1973).

Fan deposits begin near the bedrock/colluvium boundary and extend down to the Gardner River, separated locally by colluvium-covered, bedrock-cored ridges and glacial deposits (Plate 1). Many of the fans have been truncated by the Gardner River and fan surfaces generally lie 3 to 7 m above the river. No alluvial fan deposits are present directly west of the Gardner River opposite the study site.

Gardner River deposits (F) consist of well sorted and

rounded, clast-supported gravel which contains diverse rock types. The river has cut through the fan deposits creating small, sometimes terraced floodplains which are a meter or less above the Gardner River and occur between the Gardner River and scarps adjacent to and directly east of the river (Plate 1). The river gravel is younger than all of the fan deposits with the possible exception of fan deposits which occur between scarps and the river (Plate 1).

Landslide deposits (Ls) occur in areas of colluvium, contain fresh scarps, and do not contribute appreciable sediment to the fans (Plate 1). Alluvial fan deposits cover the toe of a large landslide deposit located in the southwest portion of the study area (Fig. 4 and Plate 1).

Faults

Two pieces of field evidence indicate that a fault does not exist between the steep west face of Mt. Everts and the alluvial fans. First, no offset was found in fan or glacial deposits present at the base of Mt. Everts. Second, lithologic characteristics and unit thicknesses noted in the study area correlate with stratigraphically complete sections of the Cretaceous Frontier Formation through Cretaceous Everts Formation interval measured by Fraser and others (1969). The nearest fault of significance to the fans is the Lava Creek fault which parallels the Gardner River about 0.6 km west of the study site (Pierce and others, 1991). This fault is a

north-trending, high angle reverse fault dipping below Mt. Everts with an estimated stratigraphic throw of 600 m (Fraser and others, 1969). North-south-oriented normal faults occur just to the west of the Lava Creek fault and show kilometer-scale displacements; however, only one exhibits evidence of Quaternary movement (Pierce and others, 1991).

The steep west flank of Mt. Everts is primarily the result of erosion, not faulting. Prior to 11,000 years ago, the Gardner River valley in the vicinity of the study area contained an 800 m-thick glacier which covered Mt. Everts (Pierce and others, 1991). Study-area alluvial fan formation began after de-glaciation of the Gardner River valley which exposed the mudrock-dominated, steep, west flank of Mt. Everts. Though faulting has not directly influenced the fan environment since de-glaciation, normal faulting west of the Lava Creek fault may have played a role in causing base level changes in the Gardner River which has indirectly affected fan development.

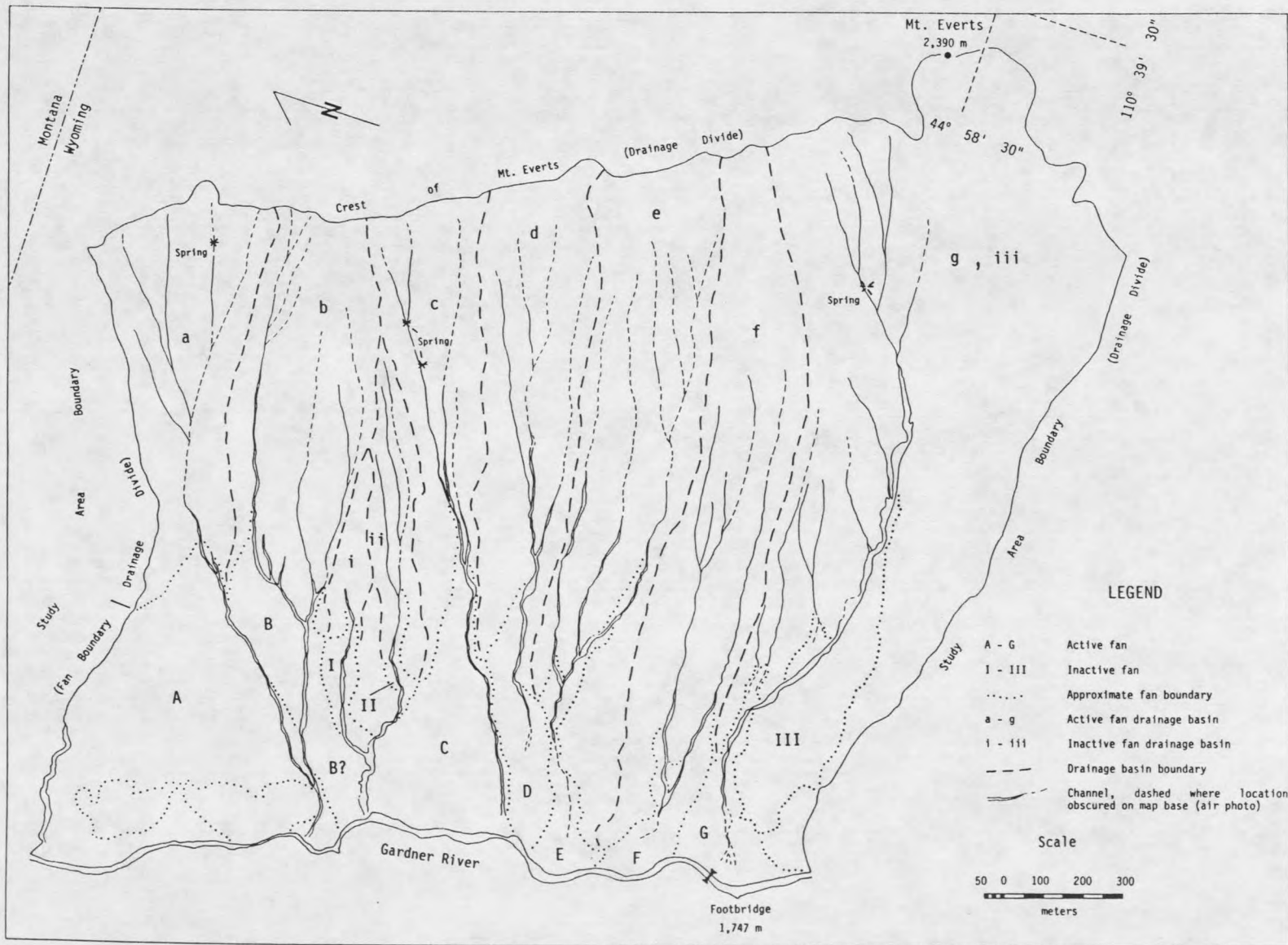
Fan Drainage Basins

Figure 7 shows the outline of the seven active (A-G) and three inactive fans (I-III) and their drainage basins, a-g and i-iii, respectively. Drainage basin areas range in scale from 1,000's m² (i) to about 0.5 km² (g, iii). The drainage basin labeled "g, iii" is the drainage basin for fan G (active) and

fan III (inactive). The position of fans G and III and the spatial pattern of their surface deposits indicate that these two fans have received most of their sediment from the channel which now debouches onto fan G. The portion of drainage basin "g, iii" south of the channels on Figure 7 is well vegetated with conifers, shrubs and grasses and does not appear to currently contribute a significant amount of sediment to fan G.

Nearly all of the sediment delivered to the fans comes from the steep, sparsely-vegetated, upper portions of the fan drainage basins. That portion of the fan drainage basin which occurs from the crest of Mt. Everts, which forms the upper drainage divide for the fan drainage basins (a-f; g,iii), down to just above the fan apexes is hereafter designated as the upper-fan drainage basin (Fig. 7). Slope angles in the upper-fan drainage basins range from 30 to 35°. Evidence that fan sediment is derived from the upper-fan drainage basins includes the presence of rills and gullies and the near absence of vegetation. Conversely, areas below fan apexes (fan surfaces, glacial and landslide deposits) do not exhibit appreciable rills or gullies and are stabilized by vegetation.

Figure 7. Map showing outlines of the seven active (A-G) and three inactive (I-III) fans and their drainage basins, a-g and i-iii, respectively. Map distances above the fan apexes may be distorted by as much as +44%; see METHODS section for explanation.



Erosion has occurred on the fan surfaces where the active fan channels are incised and their bed lies below the fan surface. However, the area covered by incised portions of fan channels is much less aerially extensive than the area covered by the upper-fan drainage basins (Fig. 7). Also, field reconnaissance of active fan channels which experienced debris flows after storm events during the Summer of 1992 revealed sporadic occurrence of fresh debris-flow deposits along the channels from the terminal debris-flow deposit to the upper portion of the fan drainage basin. This indicates that these debris flows originated in the upper portion of the fan drainage basin.

In an inventory of land erodibility in the upper Yellowstone River drainage basin, Shovic and others (1988) grouped the upper portion of Mt. Everts with the most erosive lands in the region, classifying it as "highly erosive." Several of the fan drainage basins on the upper portion of Mt. Everts are spectacular, precipitous, barren, funnel-shaped amphitheaters (Figs. 2-3). Comparison of Figures 6 and 7 demonstrates that the upper drainage basins or sediment source areas for the fans are carved into the highly erodible, jointed mudrock and sandstone of the Everts Formation and Eagle Sandstone. The two steeply dipping joint sets which intersect at high angles may significantly increase the erodibility of rocks in the study area. Lab and field studies show that rock erodibility may be more strongly influenced by

jointing or fracturing than rock type (e. g. Hooke and Rohrer, 1977).

A very small amount of fan sediment originates on the low-lying, east-west-trending, colluvium-covered ridges cored by Telegraph Creek Formation and Cody Shale (compare Figs. 6 and 7). North-facing slopes support thick mats of grasses and show no evidence of erosion. However, south aspects are often rilled and only sparsely vegetated with grasses which typically grow in clumps on soil pedestals (centimeter-scale). Pedestals may indicate sheet erosion (Dunne and Leopold, 1978) and/or raindrop erosion (Ellison, 1948). Though rill erosion and possibly sheet and/or raindrop erosion probably occur on south aspects of low-lying ridges between the fans, no fresh, unvegetated, sediment deposits could be traced to, or were observed near the south-facing ridge bases.

The fan drainage basins produce both fine (mud to sand) and coarse (gravel) sediment. Fine sediment is weathered from the mudrock-dominated Everts Formation in the upper catchments and accumulates in hollows, gullies and on the steep, barren slopes (Fig. 8). Angular sandstone clasts spall from highly jointed outcrops of Eagle Sandstone and choke lower-catchment channels above the fan apexes (Fig. 9).

Debris flows originate above the fans and frequently transport the fine and coarse sediment which has accumulated on steep catchment slopes and gullies out of the fan drainage basins and onto the fans. Narrow, steep-sided levees observed



Figure 8. Upper-fan drainage basin slope. The steep, nearly barren upper portions of the fan drainage basins are underlain predominantly by mudrock of the Everts Formation which rapidly weathers to produce a layer of fine-grained regolith. View is to the south in the upper, northeast portion of drainage basin g, iii.

in the upper portions of the catchments are evidence that debris flows originate high in the catchments. After descending the upper catchment, debris flows engulf accumulations of gravel-sized sandstone blocks in the lower



Figure 9. Large sandstone boulders in one of the main channels above fan E. Base of the Eagle Sandstone visible in upper right portion of photo. Long axis of the two large boulders in foreground is about 1.5 m.

catchment channels and flow out onto the fans.

Debris flows are probably initiated with higher frequency near spring and seepage areas which occur in some of the study-area fan drainage basins (Fig. 7). Field reconnaissance of the study-area fans revealed that fans supplied by sediment

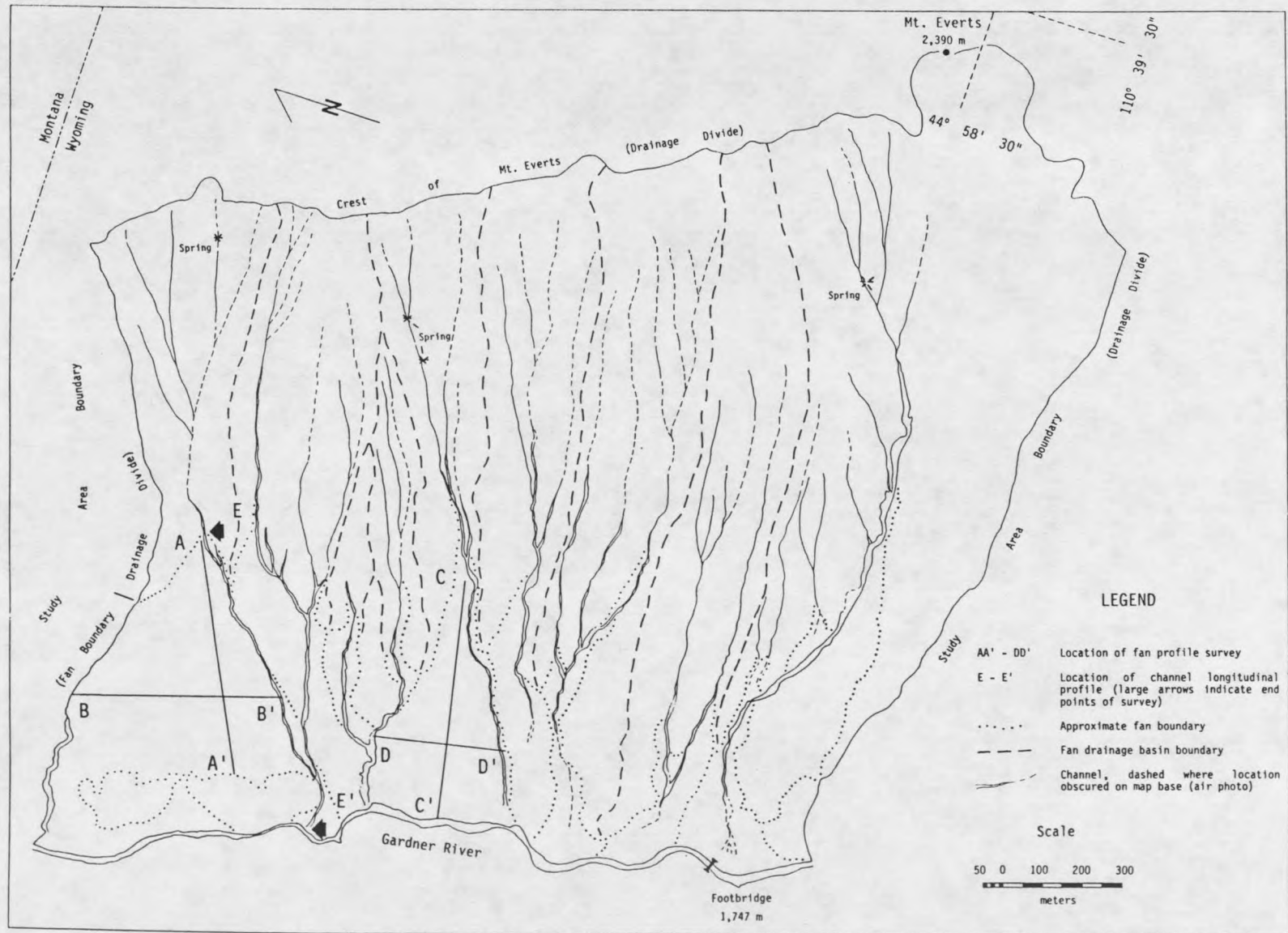
from drainage basins which contain springs (A, C, G; Fig. 7) exhibit a greater abundance of recent, unvegetated, debris-flow deposits on their surfaces than the other fans. Increased sediment production near spring and seepage areas likely results from constant wetting of rocks by springs and seeps which enhances mechanical and chemical weathering processes (Griggs, 1936; Bunting, 1961; Sharp, 1976; Smith, 1978; Higgins, 1984).

ALLUVIAL FAN MORPHOLOGY

Overall fan morphology is characterized using a map of fan outlines which shows fan size and plan-view shape, two fan longitudinal and two cross-fan profiles, and an estimate of fan thickness. Outlines of seven active (A-G) and three inactive (I-III) fans are shown in Figure 7. Location of fan boundaries are based on the pattern of channels and deposits documented in the detailed map of the fan surfaces (Plate 1). Active fans are those which display recent, unvegetated deposits.

To optimize the usefulness of the results, the largest two fans in the study area, fans A and C, were surveyed to obtain longitudinal and cross-fan profiles (Fig. 10). Measurement of the larger fans is adopted because geomorphic studies of fans cited in the literature are predominantly from fans larger than any of those found in the study area (e. g. Bull, 1964; Denny, 1965; Harvey, 1990; Mukerji, 1990). Thus the larger fans form a better comparative data base. No other fans in

Figure 10. Map showing location of cross-fan and longitudinal profiles of fans and channel longitudinal profile. Map distances above the fan apexes may be distorted by as much as +44%; see METHODS section for explanation.



the study area are as large as fans A and C, with the possible exception of fans III and B. Fan III formed on the toe of a large landslide deposit, and therefore its overall morphology is not representative of a fan. Longitudinal and cross-fan profiles of fan B would yield questionable data because the western half of fan B (labeled "B?") may actually represent a portion of fan A.

Longitudinal profiles were surveyed from fan apexes to the center of distal-fan boundaries. In the case of fan A, a deep, relict channel occupies its center line (see Plate 1), so a longitudinal profile line was surveyed on the southern half of the fan.

Size and Plan-View Shape

The study area contains a wide variety of fan sizes and shapes (Fig. 7). Individual fans range in size from about 0.008 km² (fan II) to 0.22 km² (fan A above glacial flood deposits, compare with Plate 1). The plan-view shape of the fans shown in Figure 7 has been influenced by the Gardner River and glacial deposits (Plate 1). The distal ends of fans B-G have been truncated by the Gardner River leaving scarps several meters high along the east bank of the river. Lateral growth of fans E and F, and I and II is restricted by a deposit of glacial till between them (Plate 1).

The longitudinal extent of fan A was impeded by a 40 m-

high ridge of glacial flood deposits (two irregular, circular shapes at the distal end of the fan; see Fig. 7 and Plate 1) which created a barrier for fan sediment. This ridge was later dissected and a smaller fan formed at the base of the glacial flood deposits (Plate 1).

The Gardner River reduces the longitudinal extent and therefore size of the fans. The study-area fans accumulated in a relatively narrow corridor between the base of Mt. Everts and the Gardner River (Plate 1). Much of the sediment transported down active fan channels discharges into the Gardner River which transports sediment away from the fans. In order for the study-area fans to increase their extent distally, the rate of fan deposition must exceed the rate of erosion by the river. Because the river has truncated portions of all the active fans (A-G), thereby reducing their size, the rate of erosion by the Gardner River has recently exceeded the rate of fan deposition.

Cross-Fan Profiles

Two cross-fan profiles were surveyed midway between fan apexes and distal-fan terminations (Figs. 10-11). Cross-fan profile endpoints coincide with lateral fan boundaries. The cross-fan profiles of fan A and C exhibit a convex-upward shape (Fig. 11). Cross-fan profiles are convex-upward because deposition occurs more frequently along the longitudinal

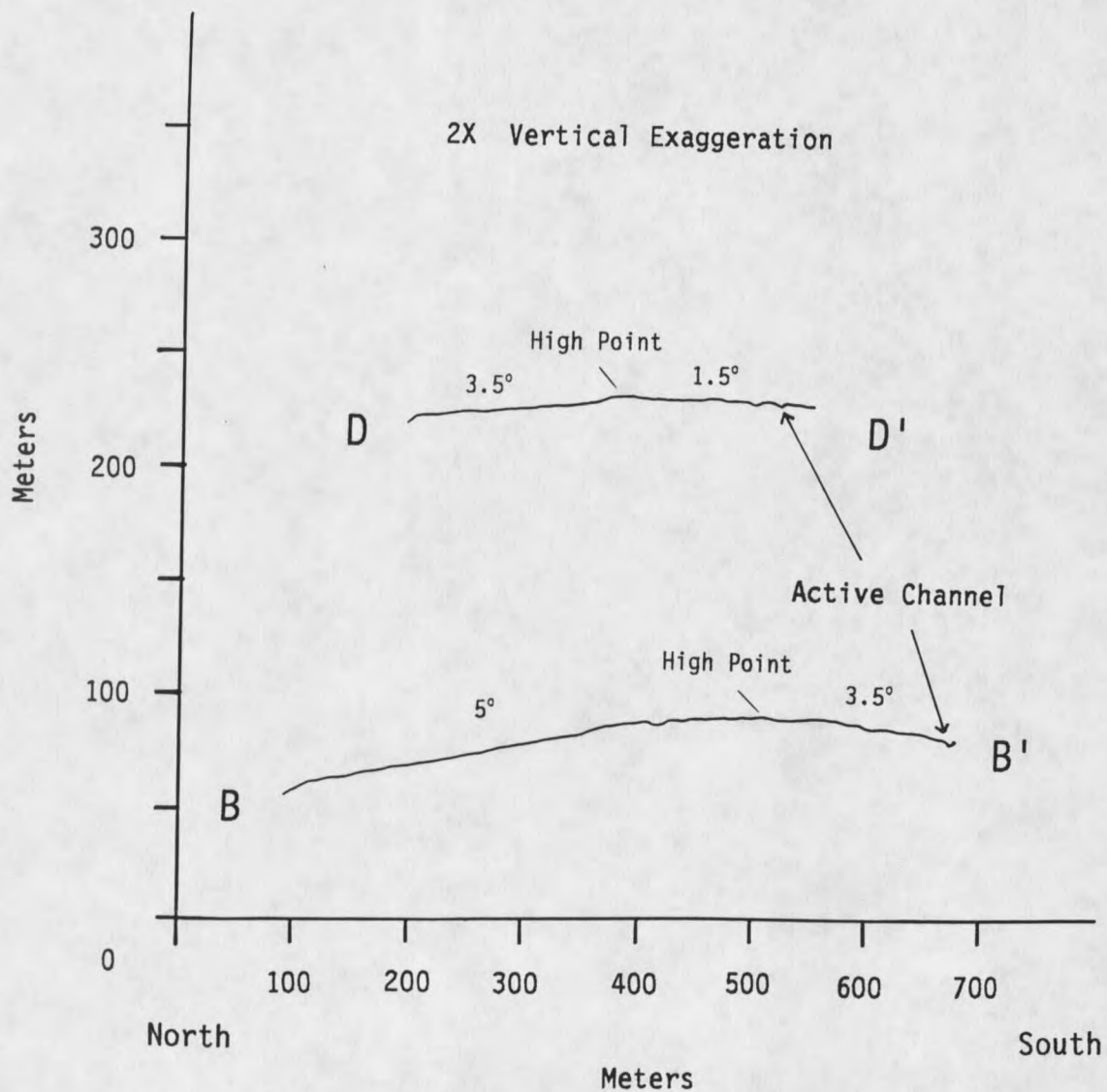


Figure 11. Cross-fan profiles of fans A and C shown at 2X vertical exaggeration. Angles refer to the fan gradient along the cross-fan profile from the topographic high point to the lateral fan edge. Cross-fan profile locations are shown in Figure 10.

center of an alluvial fan (Bull, 1964). The active channel for both fans is presently located along the southern fan edge (compare Figs. 10 and 11). Meter-scale irregularities on the profiles represent fan channels and deposits.

Both profiles display steeper northern than southern lateral slope angles measured from the topographically highest point on the cross-fan profile to north and south lateral fan edges (Fig. 11). The northern lateral slope angle of fan A is 5° while the southern lateral slope angle is 3.5° (Fig. 11). The northern lateral slope angle of fan C is 3.5° , while the southern lateral slope angle is 1.5° (Fig. 11).

The study-area fans are actively coalescing to form a bajada or apron of alluvial sediment. Lateral fan coalescence has produced lower cross-fan profile slope angles on the southern sides of fans A and C. During the initial development of fans A and C, lateral fan expansion was unimpeded by other fans. Prior to coalescence, conical-shaped fans tend to exhibit convex-upward cross-fan profiles with nearly equal northern and southern lateral slope angles. During fan coalescence, topographic lows between fans become filled with sediment when the active fan channel switches to a topographic low between two fans altering the shape of the cross-fan profile (Bull, 1964).

As sediment fills the topographic low between two fans, the lateral fan slope angle measured from the topographically highest point on the cross-fan profile to its coalescing

lateral edge becomes smaller. In the case of fan A, the active channel is currently on the south edge of the fan, and sediment is periodically deposited in the topographic low between fans A and B. The north side of fan A does not exhibit coalescence with another fan. Therefore, the north side of fan A exhibits a steeper lateral slope angle (5°) than the south side of fan A (3.5°) which is gentler because of sediment accumulation between fan A and B (Fig. 11). The same situation is exemplified by fan C where a significant topographic low exists between the north side of fan C and fans B, I and II. Significant fan coalescence has not yet occurred in this area. However, lateral fan coalescence is occurring on the south side of fan C. The topographic low between fans C and D has received a significant amount of sediment which causes the southern lateral slope angle (1.5°) to be less than the northern lateral slope angle (3.5°) on the cross-fan profile of fan C (Fig. 11). Lateral coalescence on the southern edges of fans A and C has also caused the southern cross-fan profile endpoint to be topographically higher than the north endpoint (Fig. 11).

Longitudinal Profiles

Longitudinal profiles of fans A and C (Fig. 12) show a gentle, concave-upward shape. From apex to distal termination, the overall slope of fan A is 11° and fan C is

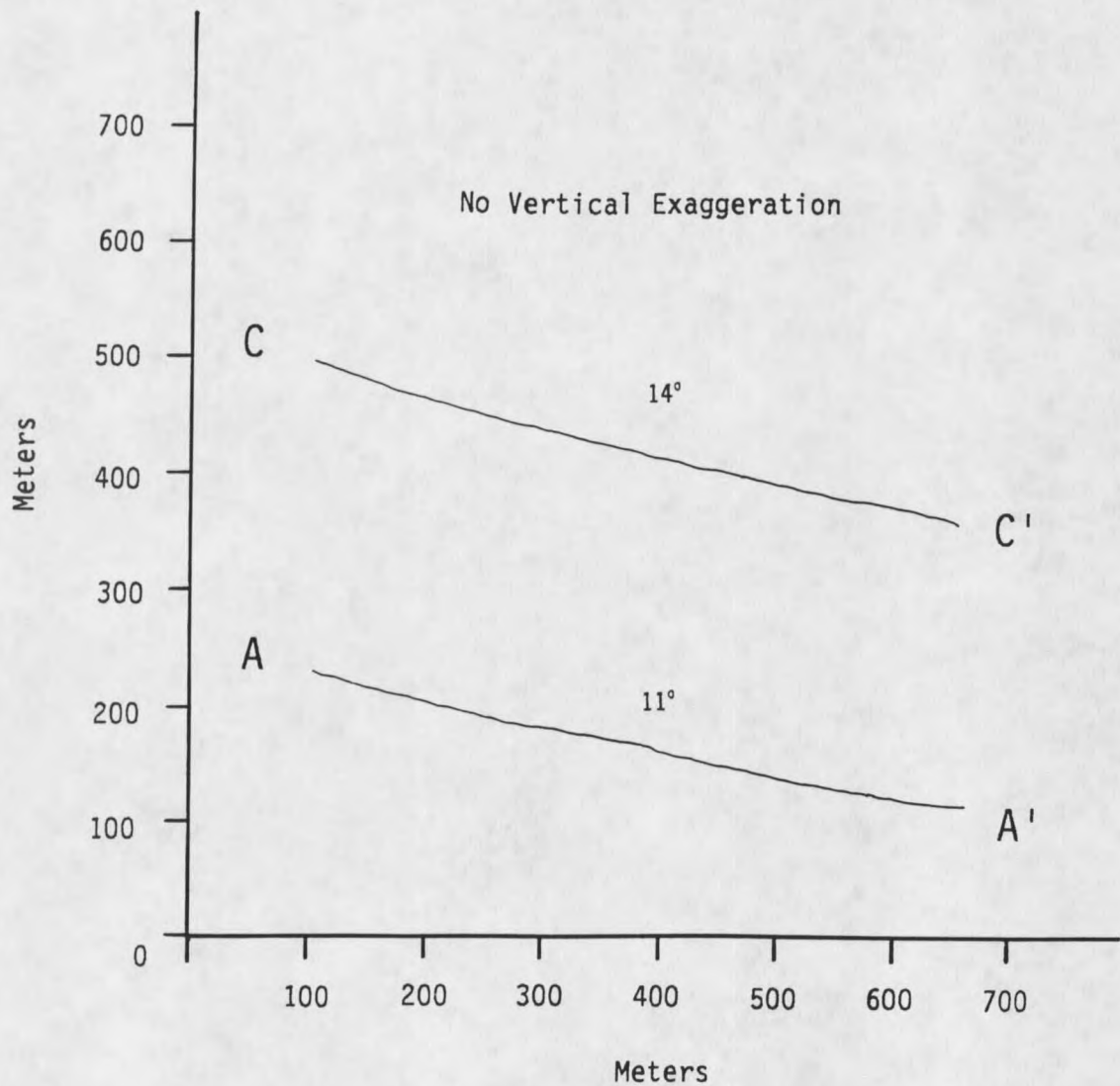


Figure 12. Longitudinal profiles of fans A and C. No vertical exaggeration. Longitudinal profile locations are shown in Figure 10.

14°. Fans exhibiting slope angles greater than 5° are considered steep (Blissenbach, 1954).

Thickness

The thickest portion of the fans should occur in their medial section at the unfaulted, topographic break between the base of Mt. Everts and the Gardner River channel. Study-area fan thickness decreases toward the apex as demonstrated by bedrock exposed in fan channel bottoms at or immediately above fan apexes. Evidence that the fans thin distally includes surface exposure of the Frontier Formation on both edges of the Gardner River channel and an exposure of Cody Shale which occurs in the distal active channel of fan A, only 2 to 3 m below the fan surface. (This exposure of Cody Shale is located at the 15° dip measurement near the northwest corner of the geologic map (Fig. 6)). Bedrock does not crop out near the medial portions of the study-area fans.

Minimum thickness for the thickest portion of fans A and C can be estimated using their cross-fan profiles. Thickness is estimated by projecting a +1° line from the north end point of the cross-fan profile to below the highest point on the cross-fan profile. The +1° line projected beneath the fans is used to estimate the slope of the pre-fan landscape (glaciated valley floor) which is best approximated by the current gradient of the Gardner River channel. This method of

estimation yields thicknesses of 33 m for fan A and 10 m for fan C. Fan A is the largest in the study area and represents the thickest accumulation of fan sediment.

ALLUVIAL FAN SURFACE MORPHOLOGY AND SEDIMENTOLOGY

The primary objective of detailed fan surface mapping is to characterize sedimentologic and morphologic attributes and spatial distribution of study-area fan deposits and channels. These data can be used to interpret fan sediment transport processes (Costa, 1988). Study-area alluvial fan surfaces are covered by a myriad of channels, and matrix- to clast-supported debris-flow levees and lobes which form distributary patterns pervasive on all of the fans (Plate 1). Low-relief, planar surfaces are much less aerially extensive and possess little to no gravel-sized sediment. These flat areas are interpreted as probable sheetflow deposits from unconfined, sediment-laden water or hyperconcentrated flows. Relief on the fan surfaces ranges from 12 m-deep incised channels to 2 to 3 m-high levee and lobe deposits. The occurrence of numerous depositional events during the period of study and within the last several years presented an excellent opportunity to evaluate and compare morphologic and sedimentologic characteristics of both recent and older fan deposits.

Debris-Flow Deposits

Debris-flow deposits display unique surficial sedimentologic and morphologic characteristics (Bull, 1972; Nilsen, 1982; Costa, 1984, 1988) which are ubiquitous features of the study-area alluvial fans. Debris-flow deposits are dominantly matrix- but may be clast-supported, very poorly to poorly sorted, and consist of mud to 2 m diameter boulder-sized particles. Clasts are very angular to sub-rounded sandstone with lesser amounts of shale, mudstone, welded tuff and andesite. Lithology of clasts contained within the deposits indicates that clasts are derived from rock outcrops on the upper portion of Mt. Everts (see Fig. 6 legend). Occasionally, a clast of basalt can be found in a debris-flow deposit. These basalt clasts are derived from glacial deposits which occur in the study area (Plate 1). Debris-flow deposits can be distinguished from glacial and fluvial deposits which contain an abundance of basalt, granite, limestone and other rock types brought to the study area from elsewhere. Debris-flow matrix is poorly sorted and contains a high proportion of mud-sized particles. Evidence that mud imparted appreciable shear strength to the flows includes boulder-sized particles floating in fine-grained matrix and steep deposit margins. Branches, twigs, conifer cones and fragile clasts of coal (derived from the Eagle Sandstone)

commonly occur in the deposits and would be destroyed or washed away if the sediment was moved by turbulent water or hyperconcentrated flows (Sharp and Nobles, 1953; Johnson, 1970). Debris-flow deposits were mapped as either levees or lobes based on differences in morphology.

Levees

Levees continuously to discontinuously line active and relict fan channel edges (Fig. 13) and bottoms and are present at proximal- to distal-fan locations (Plate 1). One or both channel edges may display levee deposits. Levees also occur in the upper portions of the fan drainage basins. Levees are



Figure 13. Two cobble- and boulder-rich levees (lv) lining a relict channel (rc) on fan A. Sagebrush is about 60 cm tall.

broadly convex to sharp-crested ridges of sediment tens of centimeters to 3 m high, tens of centimeters to 20 m wide and 1 to 750 m long. Levees often occur atop one another, so mapped levees could actually represent a complex formed during several different debris-flow events.

Levees form during debris-flow events by at least three different processes. As a debris flow moves down an unconfined fan surface, cobble- to boulder-sized particles collect at the front of the flow and are constantly pushed to the margins of the advancing flow, forming narrow, sharp-crested levees with steep sides (Sharp, 1942). Levees create a shallow, narrow, U-shaped channel on the fan surface which may be scoured and deepened by fluid phases of the debris-flow event or later runoff or stream action (Sharp, 1942; Sharp and Nobles, 1953; Pierson, 1980). A second mode of levee formation occurs when a debris flow moves down a channel and locally exceeds the capacity of the channel. Channel overtopping by debris flows produces discontinuous levee deposition on one or both of the channel edges. Due to the high shear strength possessed by debris flows, levees preferentially form on the outside of channel meanders as a debris flow moves through a channel meander and pushes sediment to the outside bend of the curve (Costa, 1988). Based on laboratory experiments and field observations, Hooke (1967) attributes bouldery, sharp-crested levees to be formed by the process described by Sharp (1942), while levee deposits

formed by channel overtopping were generally wider and more rounded. Pierson (1980) describes a third mechanism of levee formation where an internal sorting process operates during flowage producing well-sorted cobble and boulder levees along flow margins.

Deposit morphology and sedimentology suggest that all three processes of levee formation may operate on the study-area fans. Matrix-supported gravelly levees which border channels whose beds occur on the surface of the fans probably form when debris flows move down an unconfined fan surface (Sharp, 1942), while levees which sporadically border active channels form by channel overtopping in areas of reduced channel capacity. Some moderately-sorted, cobble-rich, clast-supported levees too small to be mapped individually (Plate 1) may have formed by an internal sorting process during debris flowage down an unconfined fan surface (Pierson, 1980).

Fresh levee deposits on the study-area fans exhibit broadly convex to sharp-crested cross profiles. Deposit form appeared to depend on the fluidity of the debris flow, with broadly convex levees being the product of more fluid flows. Older levee-deposit-formation processes are more difficult to interpret because weathering, wind, raindrop and rill erosion, and soil creep may modify deposit morphology over time (Sharp, 1942; Hooke, 1967).

Lobes

Lobate deposits occur in channels and on fan surfaces (Plate 1). Lobes are tabular and flat-topped (Fig. 14 A) to upward-convex with steeply sloping edges in cross profile (Fig. 14 B). In planform, lobes are semi-circular to elongate and tongue-shaped (Plate 1). Slightly arcuate, convex downslope ridges are common on lobe tops (Fig. 15 and Plate 1). The ridges are tens of centimeters to 1 m high and are defined by cobble- to boulder-sized clasts. The downslope terminus of many lobes display a cobble and boulder, clast-supported framework. Lobate deposits are tens of centimeters to 2 m thick, 1 to 40 m wide and 1 to 300 m long. Small (<100 m) lobate deposits dominate the fans; however, some large (300 to 350 m) debris-flow lobes are present (Plate 1).

Poorly sorted, matrix-supported lobate deposits with steep margins result from visco-plastic debris flows with considerable shear strength (Costa, 1984, 1988). Steep-sided, clast-supported lobes result from clast-rich visco-plastic to pseudoplastic debris flows. Debris-flow lobes occur as a result of minor channel overtopping which produces lateral lobes and as larger, terminal, tongue-shaped lobes. A clast-supported lobe terminus (Fig. 14 A) may result from migration of the coarsest particles to the flow front, a phenomenon observed in Mount St. Helens debris flows (Pierson, 1986). These types of lobes are represented in Plate 1 by lobes with



Figure 14. Old (photo A) and recent (photo B) cobble- and boulder-rich debris-flow lobes. Photo A is from a northern, medial area of fan C, and photo B is from a proximal reach of the active channel on fan G. Square clipboard (30 cm) at lobe base in photo A for scale. Lobe in photo B is about 2 m high.

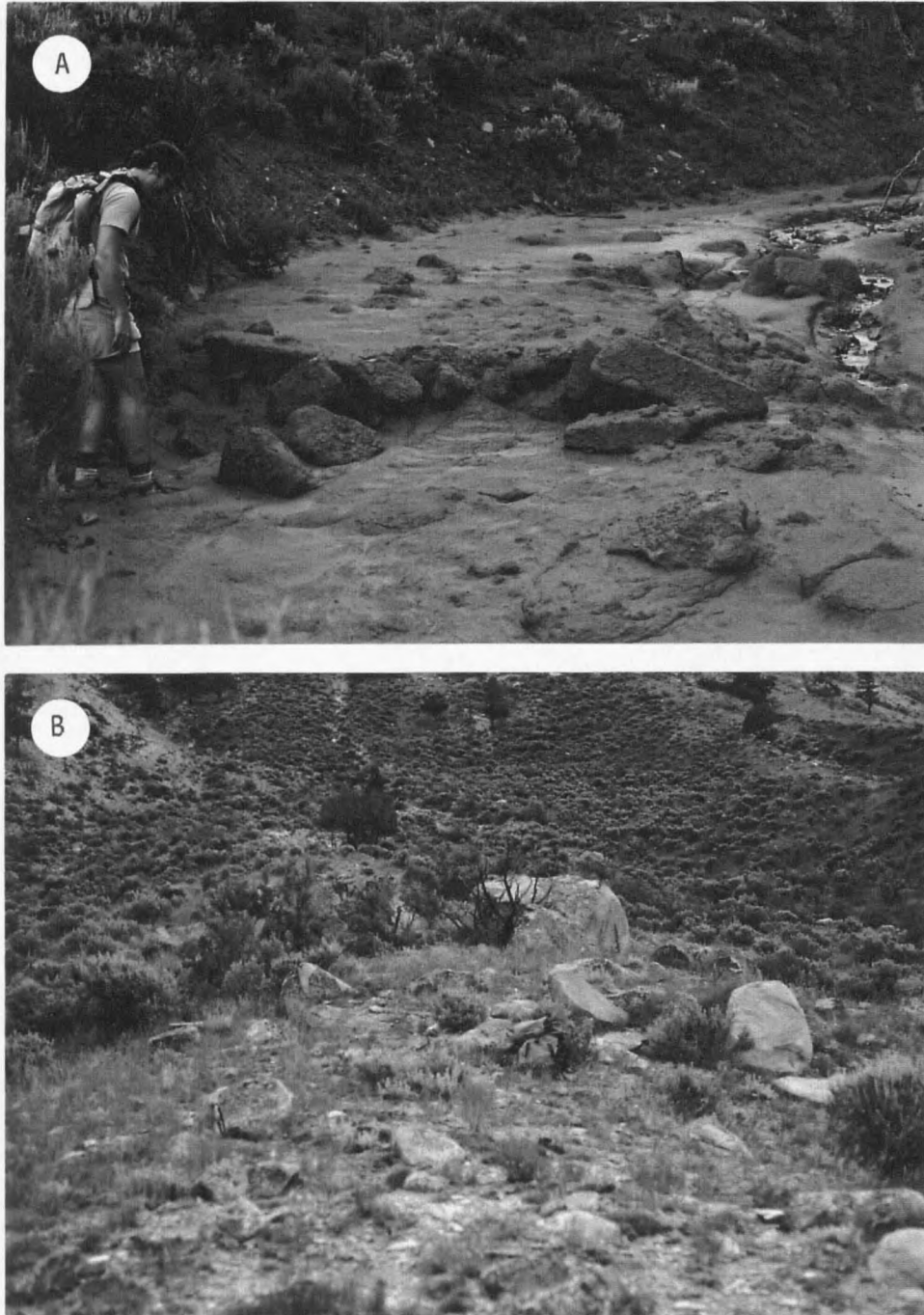


Figure 15. Recent (photo A) and relict (photo B) cobble- and boulder-rich transverse ridges on lobe tops interpreted to be from debris-flow surges. Large boulder (about 1 m high) in center of photo B is above transverse ridge and daypack is below transverse ridge. Photo A is from a medial reach of the active channel on fan G, and photo B is from the proximal area of fan D.

arcuate, bouldery ridges at their downslope termination. Arcuate, bouldery ridges not outlined by a lobate deposit contact indicate indistinct lobate forms deposited by debris flow (Plate 1).

Boulder- and cobble-rich arcuate ridges which appear within lobate deposit contacts in proximal- and medial-lobe areas are present on both fresh and older debris-flow lobe tops (Fig. 15 and Plate 1). These features have been noted on debris-flow lobe deposits by other workers (e. g. Wells and Harvey, 1987; Lawson, 1982) and are pressure ridges which form due to pulses or surges frequently observed during debris-flow events (Pierson, 1980; Jian and others, 1983).

Water- and Hyperconcentrated-Flow Deposits

Sheet-Like Deposits

Topographically featureless, nearly planar fan surfaces dominated by mud and sand with very minor amounts of small, granule- to pebble-sized particles are probable sheetflow deposits resulting from sediment-laden water or hyperconcentrated flows (Plate 1). Because water and hyperconcentrated flows possess relatively little shear strength, flows which become unconfined spread into thin sheets and leave deposits with little topographic expression (Costa, 1988). Using Hogg's (1982) sheetflow/sheetflood classification scheme, these deposits probably result from

shallow (centimeter-scale) sheetflows as opposed to catastrophic, deep (meter-scale) sheetfloods. Because the study-area fan drainage basins are relatively small, 1,000's of m^2 to about 0.5 km^2 , they are unlikely to produce an unconfined sheet of meter-scale deep water (sheetflood) on unconfined fan surfaces. However, flows may reach velocities greater than those characteristic of sheetflow (several centimeters per second) (Hogg, 1982) because the study-area fan drainage basins and fans are relatively steep, 30 to 35° and 11 to 14° , respectively.

Areas of probable sheetflow deposits could also have been formed by a single, large, clast-poor debris flow (mudflow). However, repeated deposition by mudflows which possess appreciable shear strength is expected to result in a fan surface characterized by lobate deposits.

At least four sheetflow events occurred during the Summer of 1992 resulting in thin (centimeter-scale) sheets of fine (mud- to sand-sized) sediments which cover portions of nearly flat fan surfaces (Plate 1). Figure 16 shows one of the sheetflow deposits at the distal end of fan G (compare Fig. 7 and Plate 1 for location). Small channels on the surface of the sheetflow deposit are evidence of post-depositional reworking by channelized water or hyperconcentrated flows (Fig. 16). Shallow trenches dug into a fresh sheetflow deposit on fan F revealed horizontally laminated mud underlain by horizontally laminated to massive sand. While debris-flow

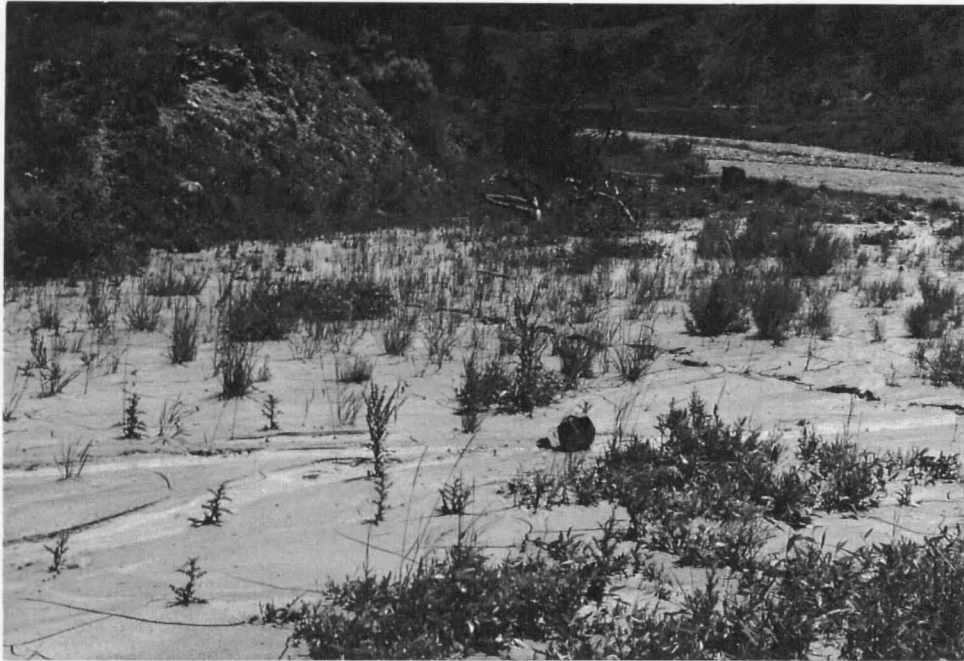


Figure 16. Recent sheetflow deposit at distal end of fan G. Small channels to left of camera case are evidence of post-depositional reworking of the sheetflow deposit by channelized water or hyperconcentrated flows. Gardner River in background. Camera case in middle ground is about 15 cm tall.

deposits generally lack internal stratification, horizontal stratification is a common feature in deposits produced by water or hyperconcentrated flows (Smith, 1986; Costa, 1988).

The aerial extent of fresh (Summer, 1992) and probable sheetflow deposits ranges from a few to approximately 14,000 m² (Plate 1). Sheetflow deposits occur primarily at distal-fan locations (Plate 1).

Sheetflow deposits result when sediment-laden water or hyperconcentrated flows leave confining fan channels and spread out onto fan surfaces. Fan channels typically become

unconfined at medial- to distal-fan areas (Hooke, 1967). At the study area however, recent, unvegetated sheetflow deposits are present in a proximal area of fan G, northeast of the proximal-medial portion of fan III (compare Fig. 7 and Plate 1). The sheetflow deposits occur at the mouth of a small mountain flank gully which becomes unconfined upon reaching a nearly flat proximal surface of fan G. Although these sheetflow deposits are included within the proximal portion of fan G, the deposits are actually separated from fan G where the active channel for fan G is bordered to the northeast for a short distance by a colluvium-covered, bedrock-cored ridge (compare Fig. 7 and Plate 1). Nevertheless, the sheetflow deposits on fan G occur topographically in a region coincident with the proximal portion of the rest of the study-area fans. This indicates that the other fans likely contain proximal sheetflow deposits as a result of small channels that debouch onto proximal-fan surfaces.

Channel Deposits

Lenticular patches of moderate to well sorted, granule to pebble gravel and sand sporadically occupy active channel bottoms and occur on the surface of debris-flow lobe and sheetflow deposits below distal-fan channel intersection points. Deposits result from channelized water or hyperconcentrated flows during runoff events or during spring-fed stream flow in channels. Lenticular channel deposits are

only centimeter-scale, were not mapped, and do not appear on Plate 1.

Channels

Active

Active, incised channels originate in the fan drainage basins and are the conduits for sediment delivered to the fans. Channels are classified as active if they can be traced from a fan to a bedrock or colluvium-covered slope above the fan. All of the channels shown in Figure 7 are active channels, and with the exception of fan I and II channels, all active fan channels contain fresh, unvegetated deposits of sediment. Evidence of channel incision includes a channel bed which lies below the fan surface and vertical to near vertical channel walls.

The active channels begin as bedrock-floored gullies which form a sub-parallel, tributary drainage pattern in the fan drainage basins (Plate 1). Drainage patterns are sub-parallel because of catchment slope steepness (Bloom, 1978), and possibly because of an east-west joint set which is approximately parallel to catchment longitudinal axes. After leaving the catchments, active channels are confined to narrow valleys by colluvium-covered bedrock ridges before reaching fans (Plate 1). Once on the fans, active channels are incised 0 to 12 m, and are 1 to 25 m wide (Fig. 17). Channels



Figure 17. Deeply incised, active, fan channel near apex of fan A bordered by bouldery levee deposits. Person standing on channel bed is about 2 m tall.

commonly have unincised reaches where they are confined only by levees less than 1 m high. Where incised, active channel walls are steep to vertical, and have been sealed with a coating of muddy sediment from recent debris-flow events. Active channel bottoms consist of hardened, compact mud- to boulder-sized sediment with sporadic occurrence of gravel lags and pockets of sand.

Channels are incised during periods of increased discharge of turbulent water or hyperconcentrated flow associated with storm-runoff events. Channel erosion may also occur during fluid, turbulent phases of a debris-flow event. In the active

channels which contain spring-fed streams, normal discharge is too small to erode the cohesive, clay-rich debris-flow sediment which contains coarse, gravel-sized particles.

Relict

Relict channels, unlike active channels, are restricted to fan surfaces and terminate on the fans in an upslope direction. Relict channels occur in proximal- to distal-fan locations and form distributary patterns on the fans. All of the channels on Plate 1 which do not appear on Figure 7 are relict channels. Relict channels are tens of centimeters to about 17 m wide, tens of centimeters to over 7 m deep and 1 to 400 m long. Nearly all relict channels, large and small, display built-up lateral margins which slope away from the channel and down to the fan surface indicating debris-flow levee deposition. Relict channels usually terminate upslope in a bouldery lobate or levee deposit and often terminate downslope in lobes or sheetflow deposits.

Shallow (< 1 m deep), U-shaped channels bordered by levees were probably constructed when a debris flow left a confining channel and moved down an unconfined fan surface (see discussion under Levees). A relict channel with a bed below a fan surface indicates that the channel was once an active channel similar to present active fan channels and stable long enough for significant erosion and incision to occur. Based on dendrogeomorphic data, Schmitt and others (1989) determined

that the position of the present active, incised fan channels has remained stable for 250 to 300 years.

Plugs

Clast-supported to clast-rich, cobble and boulder dams, hereafter called plugs, are a ubiquitous feature in proximal to distal reaches of active fan channels. Plugs span the entire width of a channel, have near vertical fronts, and rise from tens of centimeters to several meters above a channel bottom (Fig. 18). Channels become backfilled with sediment behind a plug so that the distance from the channel bottom to the top of the channel banks is decreased upchannel of the plug face.

Plugs are interpreted to form in incised channels when flowing debris encounters a stretch of channel narrower than the maximum particle size present in a flow or when several large particles or a tree fragment becomes wedged in the channel. Plugs probably form as the cobble- and boulder-rich, leading edge or head of a debris flow encounters a constricted channel reach. Boulders and cobbles may become wedged producing the clast-rich to clast-supported, coarse-gravel texture exhibited by plugs. Plugs probably form much more frequently, if not solely, during debris-flow events as opposed to hyperconcentrated or water-flow events, because of the increased capacity of debris flows to transport large



Figure 18. Large debris flow plug in the incised, active channel in the proximal area of fan G. Person (about 2 m tall) standing on top plug in channel for scale.

particles (Johnson, 1970; Rodine and Johnson, 1976) which can become wedged and block constricted channel reaches. A plug dams a fan channel resulting in channel backfilling by subsequent debris flows, sometimes causing channels to be overtopped up-channel of plugs and new channel courses to be formed (Beaty, 1963).

CHANNEL AVULSION MECHANISMS AND SPATIAL DISTRIBUTION OF
ALLUVIAL FAN CHANNELS AND DEBRIS-FLOW DEPOSITS

The spatial distribution of fan deposits is strongly controlled by the location of plugs in active fan channels. Plugs, found in all active, study-area fan channels, produce a channel segment which is unincised or a segment where channel depth is significantly reduced. This creates a channel reach with little capacity to contain debris flows. When a debris flow exceeds channel capacity and moves out onto an unconfined fan surface, subsequent flows may be diverted and a new channel path may be produced resulting in channel avulsion and a fan depocenter shift.

The active channel which forms the southern boundary of the northernmost fan (A) was surveyed from the Gardner River to the fan apex (Fig. 10) to show its step-like longitudinal profile. An abrupt drop in channel bed elevation below a plug causes the fan channel to have a step-like longitudinal profile (Fig. 19). Eighteen plugs which produce about 2 to 3 m of channel floor rise were noted along the 869 m-long channel (Fig. 19). Measurements taken above and below plugs at five locations along the profile reveal that channel depth is reduced by 0.6 to 2.6 m immediately up-channel of plugs. Reconnaissance of all active, study-area fan channels reveals

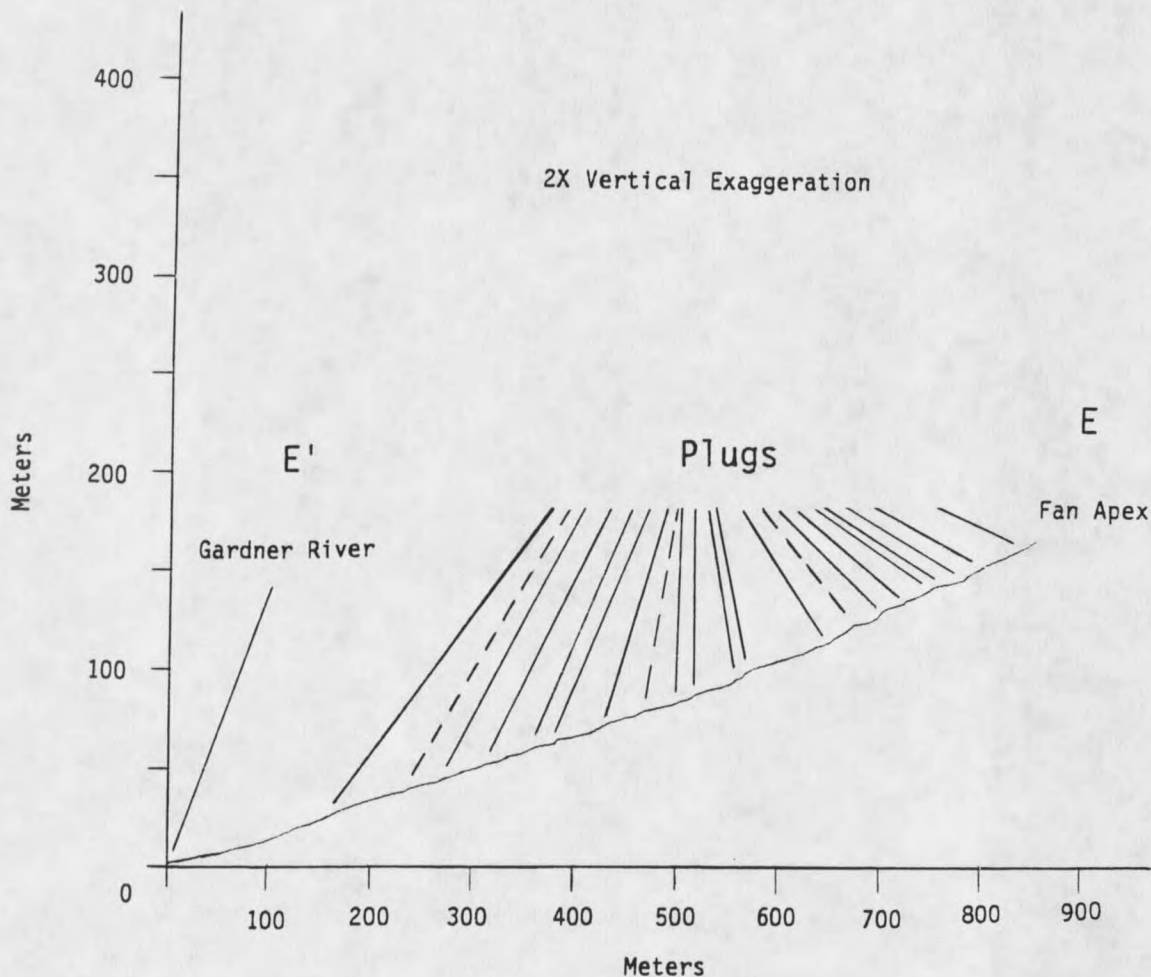


Figure 19. Longitudinal profile of fan A active channel with plug locations indicated by lines. Dashed lines indicate inferred plugs not noted during channel survey.

that they possess sites of little to no capacity due to the presence of one or more plugs. At some of these sites, fan deposition from channel overtopping by debris flows has recently taken place.

Channel avulsion is interpreted to occur in the following sequence. Channel depth is reduced due to plug formation by

a cobble- and boulder-rich, visco-plastic debris flow. This creates a site where subsequent debris-flow events may exceed channel capacity and produce radiating terminal lobes which may partially cover one another. Channel avulsion occurs above the freshly deposited debris-flow lobe(s) because subsequent flows are diverted by the fresh debris-flow lobe(s). Channel avulsion can occur in a distal-fan area because the fans are small and cobble- and boulder-rich, visco-plastic debris flows often travel the entire length of an active channel. Thus a plug may form in proximal- to distal-fan-channel reaches.

A new, active fan channel is established in two ways. Flows may follow a path determined by confining levees constructed by a channel-overtopping debris flow. Alternatively, water or hyperconcentrated flows which have been diverted from the old channel course by a debris-flow lobe(s) may erode a gully into the fan surface at a new location and create a new active fan channel.

The pattern of channels and debris-flow deposits seen on the fans is interpreted to be the result of frequent channel avulsion. Plate 1 shows fan surfaces covered by intricate, distributary patterns of channels, levees and lobes characterized by: 1) relict channels and levees which terminate upslope in a transversely-oriented levee (Fig. 20) or bouldery lobe (Fig. 21), and 2) lobes which terminate upslope in transversely-oriented channels and levees (Plate

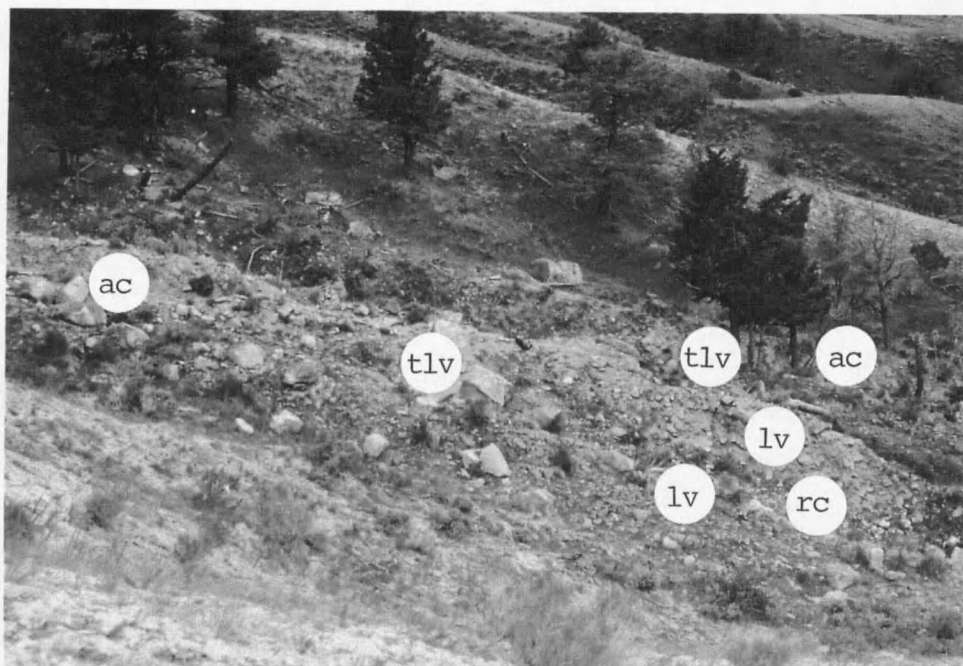


Figure 20. A relict channel (rc) with levees (lv) terminates upslope into a transversely-oriented levee (tlv) of the proximal, active channel (ac) of fan C. Daypack on "tlv" in center of photo for scale.

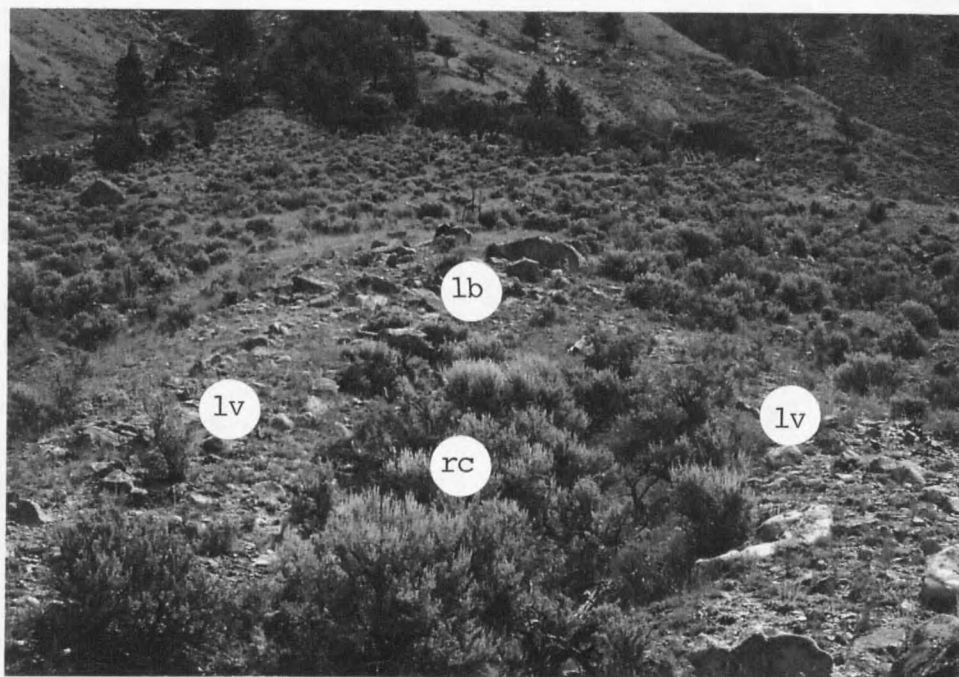


Figure 21. A relict channel (rc) with levees (lv) terminates upslope into a bouldery lobe (lb) in a medial area of fan C. Large boulder on lobe is 2 m wide.

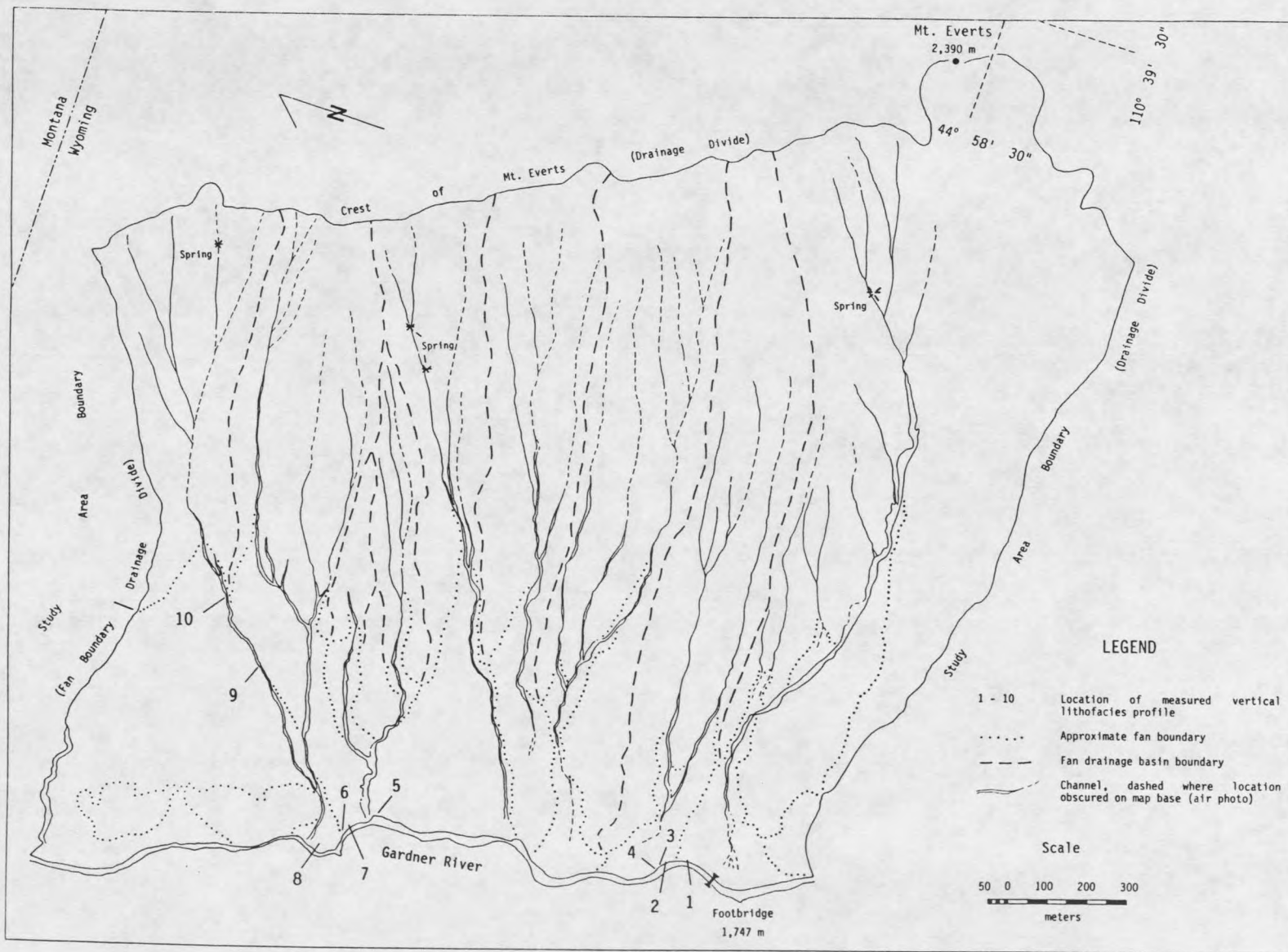
1). A channel avulsion point is located where relict channels, levees and lobes terminate upslope into transversely-oriented channels, levees and lobes. Because this pattern of deposits is easily recognizable and found on all areas of the fans, channel avulsion and depocenter shift is interpreted to be a common and frequent event at proximal-to distal-fan locations.

ALLUVIAL FAN STRATIGRAPHY

Characteristic alluvial fan sediment transport processes (water flow, hyperconcentrated flow and debris flow) can be differentiated with detailed study of sedimentologic and stratigraphic characteristics of deposits in vertical lithofacies profiles (Smith, 1986; e. g. Blair, 1987). Stratigraphy of the fan deposits was analyzed to determine the sediment transport processes responsible for internal fan deposits. These interpretations are used to determine if sediment transport processes evident from interpretation of fan surface deposits are the same as those responsible for internal fan deposits.

The location of ten vertical lithofacies profiles of fan sediment from five different fans is shown in Figure 22. Exposures of fan sediment in the study area exhibit an overwhelming preponderance of 1 to 2 m-thick layers of internally structureless, poorly to very poorly sorted, matrix-supported gravel deposited by debris flows. However,


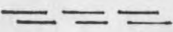

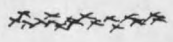

Figure 22. Map showing location of vertical lithofacies profiles constructed at natural, near vertical exposures. Map distances above the fan apexes may be distorted by as much as +44%; see METHODS section for explanation.



vertical profile sites were selected to illustrate the diversity of lithofacies displayed by debris-flow-dominated fans. Vertical lithofacies profiles were not constructed between profiles 4 and 5 (Fig. 22) because exposures of fan sediment were not vertical, making stratigraphic investigation difficult. Vertical lithofacies profiles 1 through 8 were constructed in distal-fan areas (Fig. 22) instead of utilizing incised fan-channel walls in medial and proximal areas because opportunities to study modern distal-fan stratigraphy are rare (Hooke, 1967; Nilsen, 1982). More data are needed to accurately characterize distal-fan stratigraphy.

The key for the ten vertical profiles is shown in Figure 23, followed by the ten vertical lithofacies profiles (Figs. 24-33). Based on physical characteristics, fan sediments are divided into eight lithofacies (Gms, Gmc, Gmcl, Sr, Sm, Sh, Fl, Fm). By far, the most volumetrically important lithofacies present in vertical exposures of fan sediment is matrix-supported gravel (Gms). Volumetrically important, but much less significant, are deposits of clast-supported gravel (Gmc) and massive mud (Fm). The volumetrically least significant lithofacies are horizontally laminated mud (Fl) and sand (Sh), ripple cross-laminated sand (Sr) and massive sand (Sm), and lens-shaped masses of clast-supported gravel (Gmcl). A description of the physical characteristics of each lithofacies is followed by interpretations for the origin of the deposit.

SYMBOLS

	Ripple cross-laminations
	Horizontal laminations
	Channel structures
	Plant matter
	Base of debris flow indicated by abrupt break on right edge of vertical lithofacies profiles

LITHOFACIES CODES



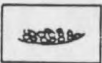


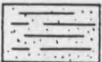


	Gms	Massive, matrix-supported gravel
	Gmc	Massive, clast-supported gravel
	Gmcl	Clast-supported, granule to pebble gravel lenses
	Sr	Ripple cross-laminated sand
	Sm	Massive sand
	Sh	Horizontally laminated sand
	Fl	Horizontally laminated mud
	Fm	Massive mud

Figure 23. Key for vertical lithofacies profiles. Lithofacies codes based on those presented by Miall (1978).

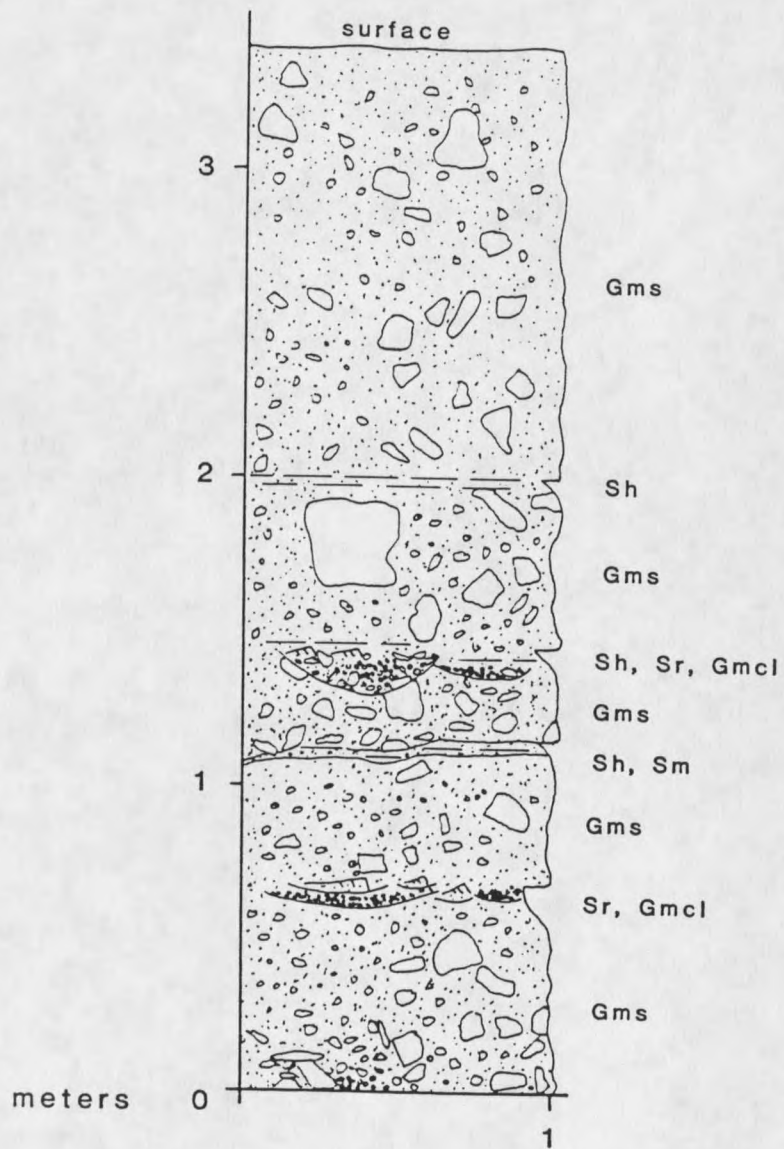


Figure 24. Vertical lithofacies profile #1.

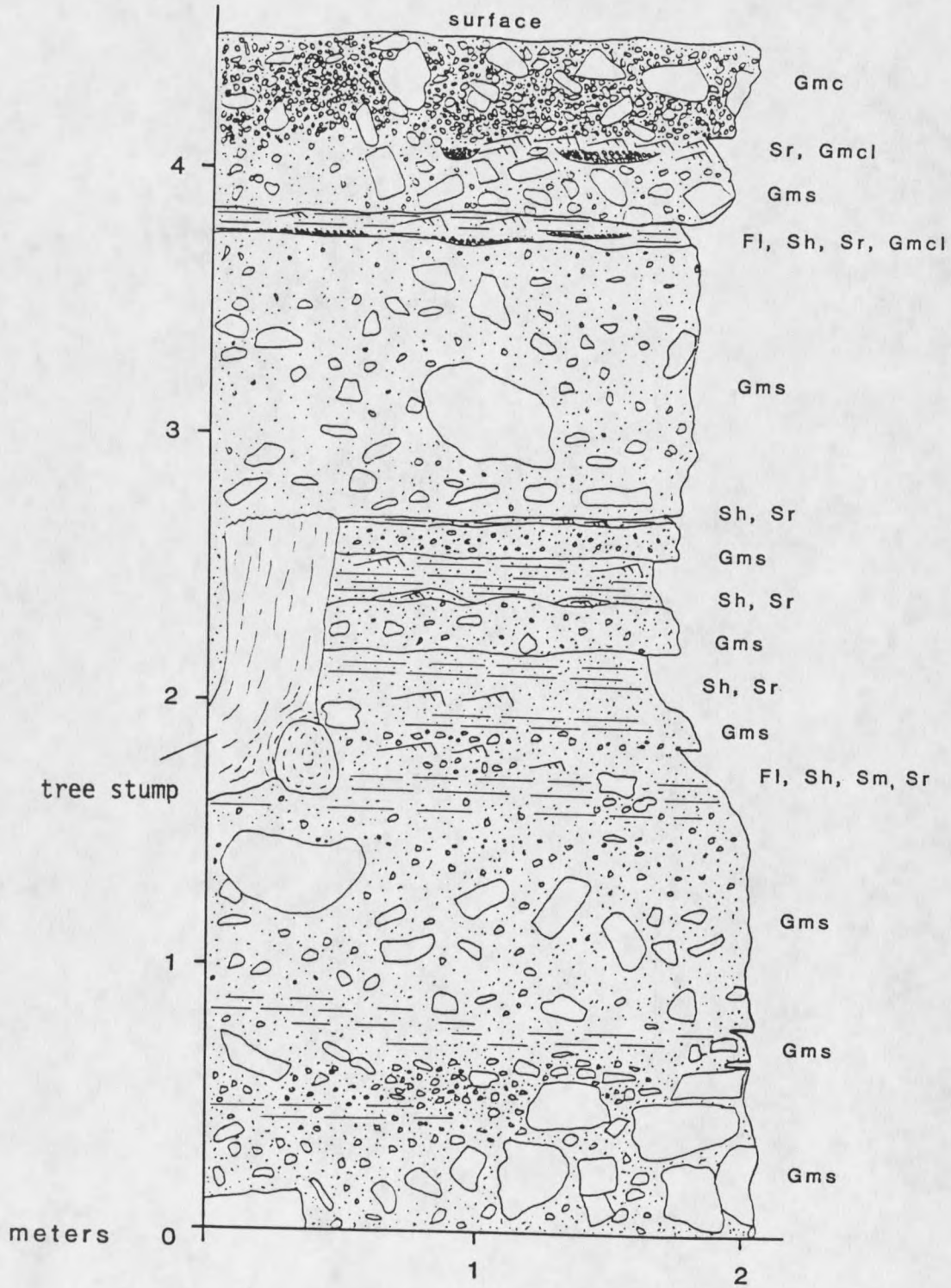


Figure 25. Vertical lithofacies profile #2.

