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

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 knv 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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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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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 km^2 area in temperate, semi-arid, northwest Wyoming to increase the accuracy and diversity of fan facies models.

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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 km^2 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.

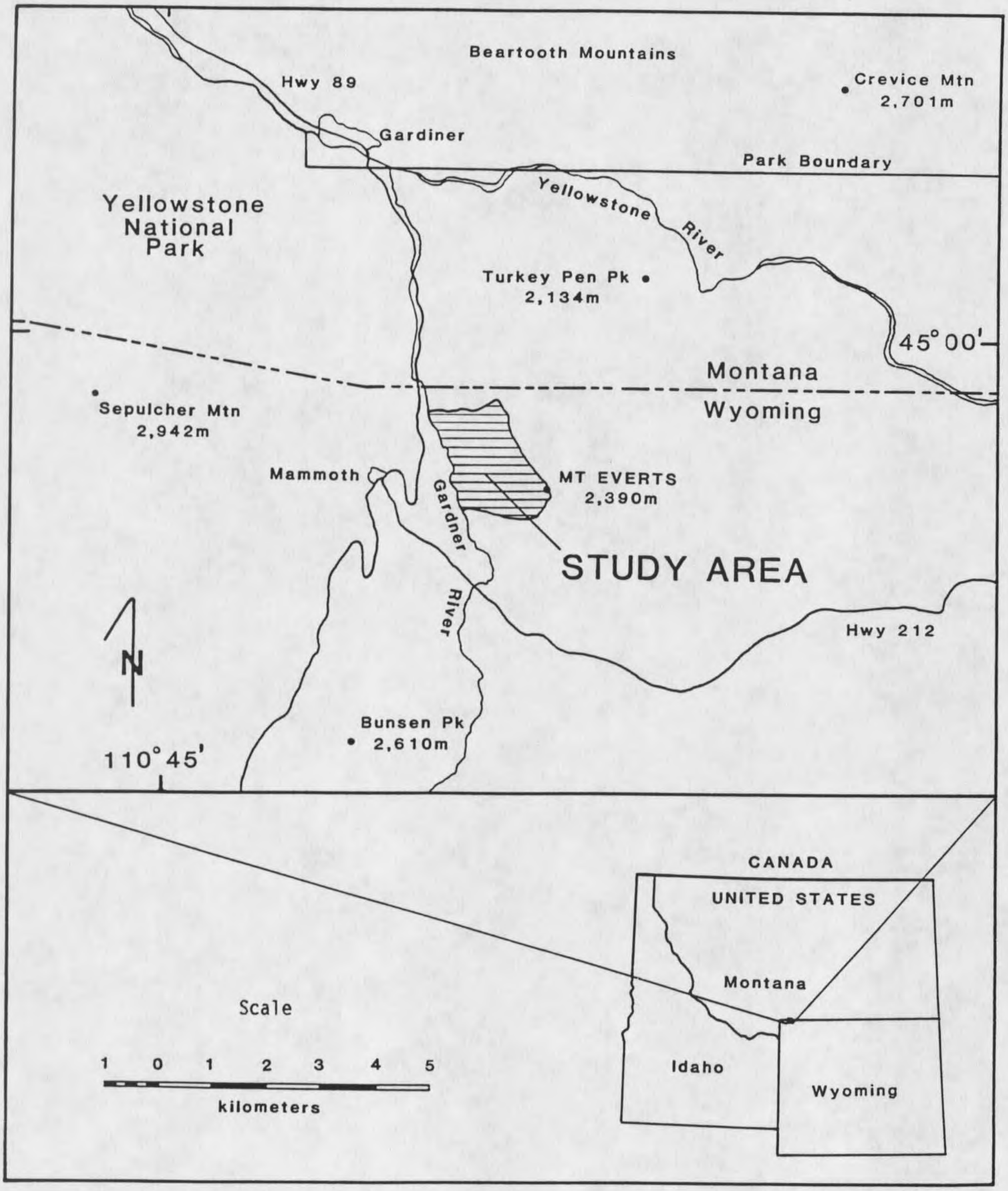

Figure 1. Map showing location of study area in the Gardner River valley along the west flank of Mt. Everts. The 1: 100,000 scale, 1986 Absaroka Beartooth Wilderness map produced by the U. S. D. A. Forest Service was used as a map base.

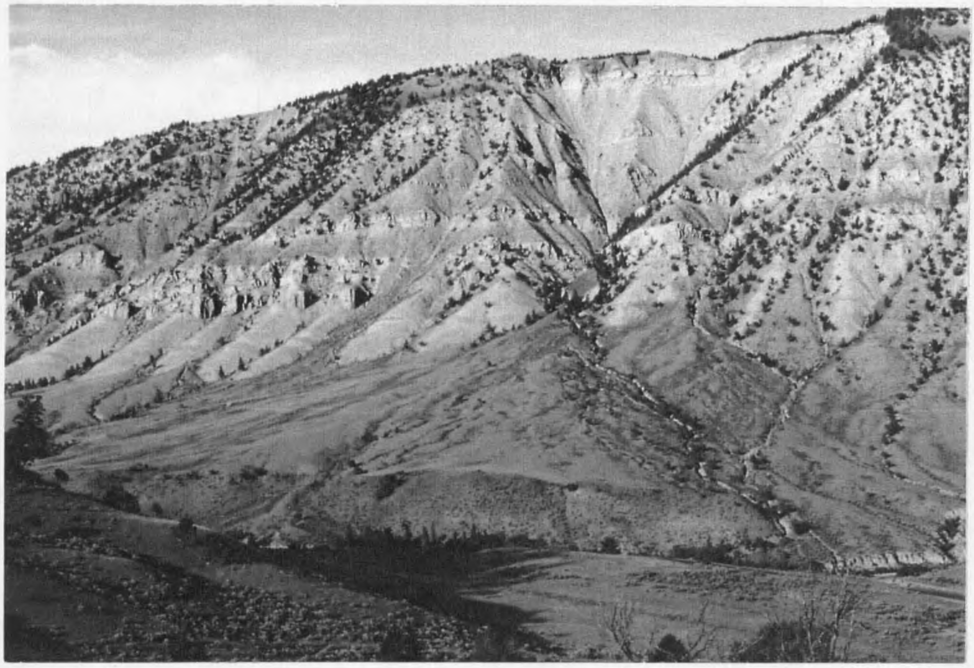

Figure 2. Northern third of study area showing debris-flow-dominated fans at the base of Mt. Everts. Left edge of large fan in center of photo is the northern study area boundary. View is to the east. Gardner River is in foreground.

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 (> 11^0) 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 (< 3^0) 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