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DEBRIS FLOW HAZARD IN THE CANADIAN ROCKY MOUNTAINS

L.E. Jackson, Jr.

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Observations on the geomorphology and sedimentology of montane fans and a methodology for the identification of debris flow hazard on fans in geologically similar northern upland areas

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1987

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CP Rail main line buried by a debris flow, Kicking Horse Pass, British Columbia, 7 September, 1987.
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DEBRIS FLOW HAZARD IN THE CANADIAN ROCKY MOUNTAINS

Abstract

Valley margins in the Rocky Mountains are locally prone to periodic inundation by debris flows. Alluvial fans and landforms and related features may be constructed by and are loci for debris flow deposition. A total of 103 fans within three areas of the Rocky Mountain Front Ranges and Main Ranges were studied in order to establish the occurrence and past frequency of debris flows. These three areas are characteristic of a wide range of physiographic settings found in the Rocky and Mackenzie mountains.

Alluvial fans and landforms, at least partly constructed by debris flows, generally have slope angles of 4° or greater whereas strictly fluvially constructed fans have angles less than 4°. Drainage basins in which debris flows reach fans at the basin mouth are predominantly smaller than 10-12 km^2 and have an internal relief of more than 500 m. Basins smaller than 1 km^2 may produce debris flows but avalanche activity is the dominant erosional, transportational, and depositional process operating in these basins. Indications of past debris flow activity include debris flow levees, bouldery terraces marking former debris flow margins, and large isolated boulders on the fan surface. Debris flow deposits in fans can be identified visually by their matrix-supported structure and texturally by the anomalous association of large components of both pebble and cobble size clasts (>2 mm ≤64 mm) and clay size (<2 μm) particles.

Debris flow hazard is best evaluated by establishing the past frequency of debris flow events. Events can be assigned maximum and minimum ages by combinations of ^{14}C dating, dendrochronology, and tephrochronology. Some of the debris flow fans studied were predominantly deposited shortly after deglaciation and have been largely inactive during the past 6600 years. Water courses crossing these fans are usually deeply incised. These inactive fans provide low hazard sites for development along otherwise high hazard valley margins.

Résumé

Par endroits, les marges de vallées dans les Rocheuses sont périodiquement inondées par des coulées de débris. La sédimentation par ces coulées de débris peut donner lieu à des formes de relief et à des cônes alluviaux ainsi qu'à des structures connexes; ces formes sont des centres d'accumulation des matériaux transportés par les coulées. En tout, 103 cônes ont été étudiés dans trois zones des chaînons Front et Main des Rocheuses afin d'établir la présence et la fréquence d'anciennes coulées de débris. Ces trois zones sont caractéristiques d'une vaste gamme de milieux physiographiques trouvés dans les Rocheuses et les monts Mackenzie.

L'angle d'inclinaison des formes de relief et des cônes alluviaux érigés au moins en partie par les coulées de débris atteint généralement 4° ou plus tandis que celui des cônes d'origine strictement fluviatile est inférieur à 4°. En général, la superficie des bassins hydrographiques dans lesquels les coulées de débris s'étendent jusqu'aux cônes à l'embouchure du bassin est inférieure à 10-12 km^2 et le relief interne, supérieur à 500 m. Les bassins qui ont une superficie inférieure à 1 km^2 peuvent donner lieu à des coulées de débris mais dans ces bassins, les avalanches sont le principal processus d'érosion, de transport et de sédimentation. Les levées érigées par les coulées de débris, les terrasses blocailleuses marquant les marges d'anciennes coulées et les gros blocs isolés à la surface des cônes sont tous des indications d'anciennes coulées de débris. Les dépôts laissés par les coulées dans les cônes se reconnaissent à l'oeil nu grâce à leur structure soutenue par la matrice, et à leur texture qui comporte une association anormale d'abondants fragments de roches de la grosseur des galets et des gros cailloux (>2 mm ≤64 mm) et de particules de la grosseur de l'argile (<2 μm).

Les risques posés par les coulées de débris sont évalués en établissant la fréquence antérieure des coulées. La datation au C^{14}, la dendrochronologie et la téphrochronologie permettent d'établir l'âge maximum et l'âge minimum des événements. L'accumulation de certains des cônes étudiés s'est produite surtout peu après la déglaciation. Les cours d'eau qui les traversent sont habituellement très encaissés. Ces cônes, en grande partie inactifs depuis 6600 ans, s'avèrent des emplacements à faible risque propices à l'aménagement le long de marges de vallées qui accusent, elles, au contraire, un degré de risque très élevé.

SUMMARY

Debris flow is a significant erosional process and depositional agent in the Canadian Cordillera. A substantial percentage of alluvial fans in the Cordillera are at least partly constructed of debris flow deposits. Many of these fans were deposited under paraglacial conditions, that is, during the period of adjustment of sediment supply and stream flow from glacial to nonglacial conditions following the last major glaciation. These fans may be inactive and undergoing erosion.

Aside from the direct recognition of debris flow sediments in natural and artificial exposures, fans containing debris flow sediments can be recognized or should be suspected on the basis of:

1. comparison of weight per cent clay content with pebble content;
2. fan slopes in excess of 4°;
3. debris flow topography and large debris flow rafted boulders on fan surfaces; and
4. morphometry of the drainage basin above the fan; most basins having debris flows have an area of less than 10-12 km^2 and internal relief in excess of 500 m.

Presently inactive fans are recognized on the basis of volcanic tephra near the fan surface and/or the entrenchment of the fan stream from fan head to fan toe and the truncation of the toe by the adjacent trunk stream. Active fans have stream trenches confined to the fan head. Forested fans may have on their surfaces trees that have been injured or killed by debris flows. Dendrochronology and radiocarbon dating are the best methods for establishing past debris flow recurrence frequencies.

SOMMAIRE

La coulée de débris est un important processus d'érosion et agent de sédimentation dans la Cordillère canadienne. Un pourcentage élevé des cônes de déjection dans la Cordillère se compose au moins en partie des sédiments laissés par les coulées de débris. Un grand nombre de ces cônes ont été déposés dans des conditions périglaciaires, c'est-à-dire au cours d'une période d'ajustement de l'apport sédimentaire et de l'écoulement fluviatile, lorsque les conditions ont passé de glaciaires à non glaciaires suivant la dernière grande glaciation. Ces cônes sont parfois inactifs et subissent les effets de l'érosion.

À part l'identification directe des sédiments des coulées de débris dans les affleurements naturels et les tranchées, il est possible de reconnaître ou de soupçonner la présence de cônes qui contiennent des sédiments laissés par des coulées de débris en se fondant sur les critères suivants:

1. un comparaison du pourcentage en poids de la teneur en argile et de la teneur en cailloux;
2. des angles d'inclinaison supérieurs à 4°;
3. la présence, à la surface des cônes, d'une topographie de coulée de débris et de gros blocs transportés; et,
4. la morphométrie du bassin hydrographique au-dessus du cône; la plupart des bassins qui contiennent des matériaux laissés par les coulées de débris ont une superficie inférieure à 10-12 km^2 et un relief interne supérieur à 500 m.

Les cônes présentement inactifs se reconnaissent à la présence de tephra volcanique près de la surface, ou à l'encaissement du cours d'eau de la tête au front du cône, ou les deux, et à la troncation du front par un axe fluvial contigu. En règle générale, on trouve les cours d'eau encaissés uniquement à la tête des cônes actifs. Des arbres endommagés ou tués par des coulées de débris sont parfois trouvés à la surface des cônes boisés. La dendrochronologie et la datation au carbone radioactif sont les meilleures méthodes pour établir la fréquence des anciennes coulées de débris.

INTRODUCTION

The Rocky Mountains have historically ranked among the more sparsely populated areas of the Earth. The larger towns or cities that have been established in this region were initially situated on bottomlands or broad terraces within major valleys.

These bottomland sites are comparatively rare in the Rocky Mountains due to the large percentage of land surface composed of summit and slope. Public works, such as roads and pipelines, new town sites and the expansion of older ones, and recreational developments, must, out of necessity, be sited along valley margins and commonly on alluvial fan landforms.

This siting frequently places these works in the path of periodic, high energy, catastrophic geomorphic processes such as debris flows, snow and rock avalanches, flash floods, and the debris they entrain. Among these hazards, debris flow is little appreciated or understood by the public or even by civil engineers and planners involved in the siting of public and private works in the Rocky Mountains.

Debris flows that reach alluvial fan landforms flow in stream courses whose geometry is dictated by water flow rather than by slurries of mud and rock. Therefore, engineered works designed to contain high water flows provide little protection from debris flows. Culverts designed to transmit flowing water are quickly plugged and overtopped by a boulder-freighted debris flow with disastrous consequences to adjacent people and property. Sites at highest risk are those located on alluvial fan landforms that are being actively built by debris flows. Evaluation of debris flow hazard must involve the identification of these sites and the documentation of past debris flow frequency.

This report presents the results of a study of alluvial fan landforms in the southern Canadian Rocky Mountains carried out during the 1979 summer field season. The results of this work, plus the contributions of others who have studied debris flows and their deposits, have permitted me to suggest a methodology for the identification of past debris flow activity and determination of past debris flow frequency for fan sites in the Rocky Mountains and other formerly glaciated, northern upland areas with analogous bedrock lithologies and structure such as the Selwyn and Mackenzie mountains.

This identification of past debris flow activity and frequency is necessary for the design of both protective structures and land use restrictions. Also required are estimates of maximum debris flow volume, instantaneous discharge, and run out distance. These latter variables require detailed studies of sediment source areas within basins plus a compilation of regional debris flow experience. They are not dealt with in this paper.

Acknowledgments

I would like to thank Mr. Tom Oddie for his diligent work as field assistant for this project. This project benefited from numerous discussions with others involved in

similar studies; I would like to acknowledge June Ryder, Geri Eisbacher, Mike Wilson, Chester Beaty, and Glen MacDonald in this regard. I would also like to thank Parks Canada for allowing me the privilege of working and sampling within Banff and Yoho National Parks. This manuscript benefited from rigorous reviews by Stephen G. Evans and David R. Sharpe; their efforts are gratefully acknowledged.

DEBRIS FLOW – DEFINITION, DESCRIPTION, AND ORIGIN

Debris flow signifies both a geomorphic phenomenon and the sedimentary deposit that it creates. The phenomenon of debris flow has been defined by Johnson and Rahn (1971, p. 169) as "...the mass movement of granular solids containing relatively small amounts of admixed water and/or air". Once initiated, a debris flow usually advances downslope as series of separate pulses or waves which overtake one another. The snout of an advancing debris flow is commonly described as a low wall of boulders and mud (e.g., Beaty, 1963). In longitudinal profile, a debris flow is slug-like with its greatest thickness at its advancing bouldery front. It progressively tapers to a thin tail which eventually merges with the channel deposits. Debris flow operates on scales from less than 1×10^{-1} m^3 (Rodine, 1975) to 1×10^8 m^3 in the case of the debris flow on the North Fork of Toutle River which was triggered by the 1980 eruption of Mount St. Helens in Washington State, U.S.A. (Janda et al., 1981; Cummans, 1981). Debris flow can transfer large amounts of sediment from mountain side to valley bottom over short periods of time – often in a matter of minutes. Many years may be required for stream erosion and transportation to move an equivalent amount of sediment in the same basin. In fact, debris flow may account for almost all the sediment transported from basin to fan in some mountain basins. For example, two pulses of debris flow occurred in the Kicking Horse Pass area of British Columbia in September 1978. These flows closed the Trans-Canada Highway for two days and the Canadian Pacific rail line for a week (Jackson, 1979). In the space of about one hour they transported an estimated 1.75×10^5 m^3 of bouldery sediment up to 3 km (Fig. 1). Approximate flow velocities were 0.3 m/s for the initial pulse and 6 m/s for the subsequent one. The stream that normally drains this basin is ephemeral with flows so small that surface flow rarely reaches Kicking Horse River and sediment transport is practically negligible.

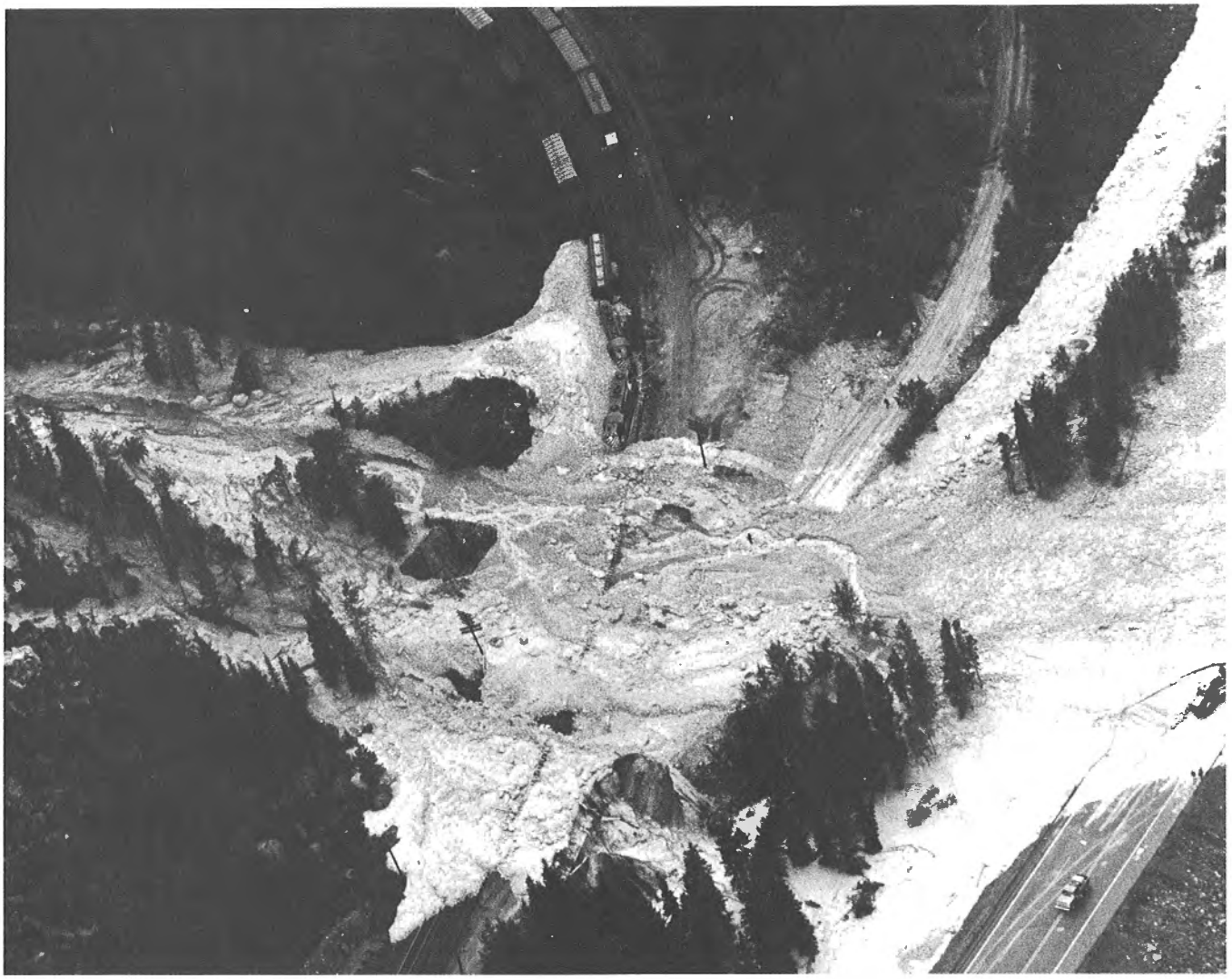


Figure 1. Debris flow triggered by a jökulhlaup from the Cathedral Glacier near Kicking Horse Pass, British Columbia, September 1978. The debris flow blocked the Trans-Canada Highway and the Canadian Pacific mainline at three locations (photo courtesy of the Calgary Herald).

Debris flow has the ability to transport very large clasts across gentle slopes. Examples are common in the literature, such as Rodine and Johnson's (1976) description of boulders with volumes of the order of 6 m^3 which were rafted by debris flow down a slope with an inclination of 5°. Figure 2 shows a similar example from Kananaskis Valley.

Two alternative flow models have emerged in the debris flow literature. These may be termed the dilatant fluid model and the plastico-fluid model. The former is an elaboration of dispersive pressure phenomena in grain flow described and investigated by Bagnold (1954, 1956, 1968). This model attributes the ability of a debris flow to raft large particles across low gradients and its bouldery snout and finer grained tail to the dispersive pressure experienced by grains in a granular material undergoing flow along a rigid bouldery. The dispersive pressure on a grain increases with the grain's surface area and the shear rate which increases towards the rigid boundary. As a consequence, large particles migrate to the flow surface and snout (Vallejo, 1979; Takahashi, 1981; Iwamoto and Hirano, 1982).

The plastico-fluid model emphasizes the density and yield strength of the muddy matrix. This model is based upon experimentation with clay, water, and sand slurried which indicated that a slurry's density and yield strength are sufficient to raft large clasts without the dispersive pressure phenomena of grain flow (Johnson, 1970; Hampton, 1975; Rodine and Johnson, 1976). Field observations of debris flows indicate that an entire spectrum of flow processes may be occurring, ranging between fully turbulent flow of grains and laminar flow of slurry-supported debris (Curry, 1966; Johnson, 1970, p. 433-459; Middleton and Hampton, 1976, p. 210; Eisbacher, 1983).

Rodine (1975), in reviewing the past literature dealing with debris flows and his own investigations, indicated that water, a source of debris containing some clay, and slopes steep enough to initiate and sustain movement are the only prerequisites for debris flow. Under conditions of dilatant fluid flow, however, clay content is not a prerequisite for debris flow. Water must be supplied at a rate in excess of the rate of its drainage away from the debris, so that pore fluid pressure is increased sufficiently to reduce the debris strength to the point that debris movement can be initiated and maintained. In the Rocky Mountains water can be supplied in sufficient quantities by direct intense or protracted rainfall, rapid ice or snowmelt, spring activity, the melting of ground ice (Owens, 1973, p. 29), or by a catastrophic event such as a jokulhlaup (glacier-outburst flood) (Jackson, 1979). Other factors, such as bare or denuded slopes, pre-existing landslides, and seismic activity, are also conducive to the occurrence of debris flow.

Upon leaving tributary valleys and entering a trunk valley, debris flows are no longer as confined and so spread out, thin, and cease to flow. Over the years, a fan-shaped landform is built by successive debris flows at such sites (Fig. 3, 4). The term *alluvial fan* is usually assigned to this landform. Since the alluvial fans investigated in this study result from both fluvial and debris flow processes, they will simply be referred to as *fans* in general or specifically as *debris flow of fluvial fans*. These fans can be made up almost entirely of debris flow material or can be built of both debris flow and fluvial sediments. Debris flow deposits are distinguished from fluvial fan sediments, by their unstratified structure and lack of sorting. They range from clay to boulders in texture and are usually matrix-supported (Fig. 5). Where they have been recently deposited on the surface of a fan, debris flow deposits are lobate with a surface relief of

Figure 2. Large boulders partly eroded from a debris flow deposit on an alluvial fan in Kananaskis Valley. Fan surface slope is approximately 4.5°. ISPG 1958-14

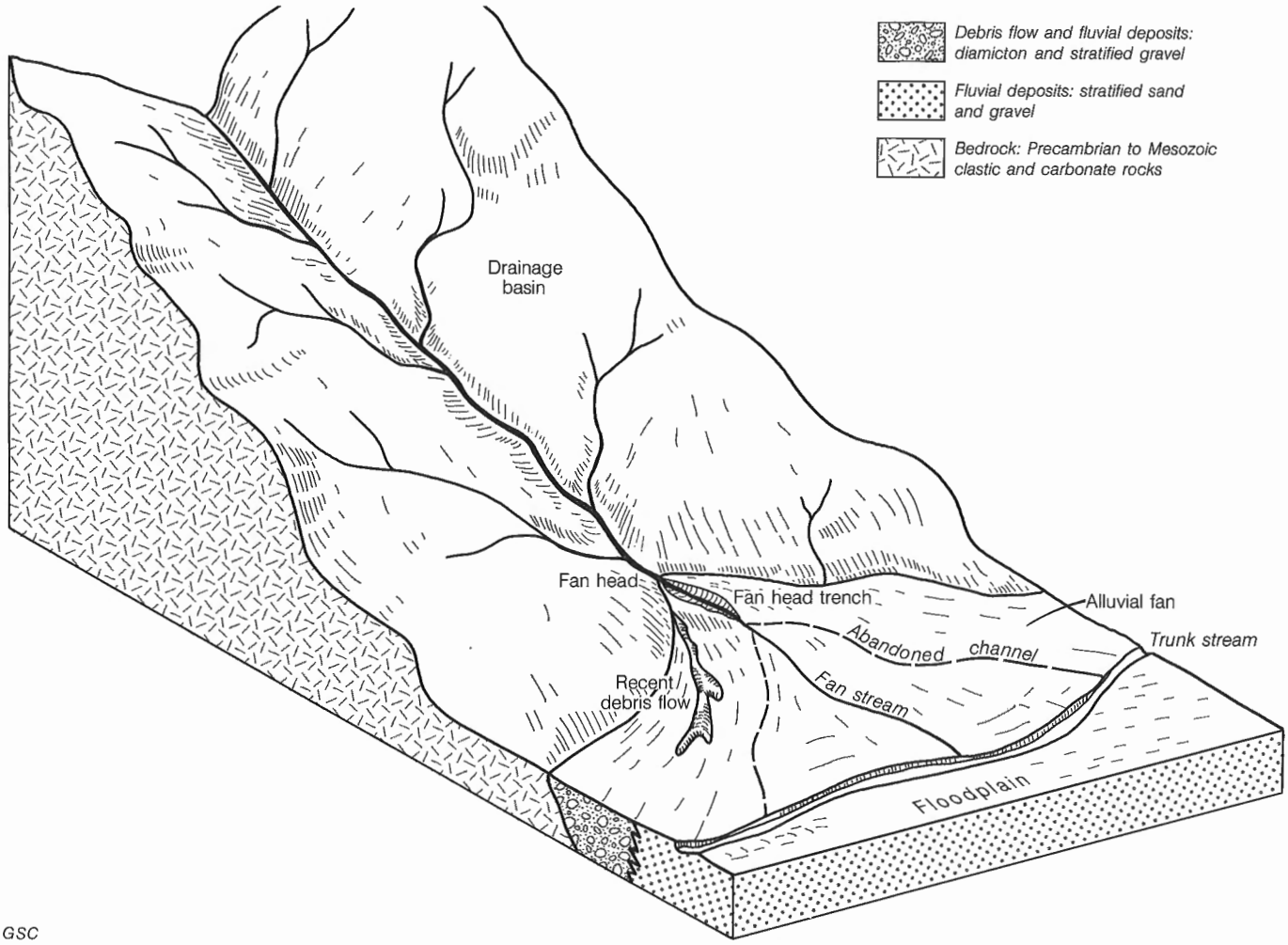


Figure 3. Idealized diagram of an alluvial fan, partly built of debris flow deposits, illustrating some of the features discussed in this report.

several centimetres to half a metre or more above the surrounding fan (Fig. 4, 5). The upper areas of the fan are frequently marked by levees left along the margin of the passing debris flow snout. Where they are interstratified with other fan sediments, debris flow deposits appear lenticular and sheet-like in transverse and axial fan sections, respectively. This is due to deposition in channels, as levees or as lobes that flowed across the fan surface thus giving an individual flow an overall shoe string morphology.

PREVIOUS WORK

Previous studies of debris flow consider either the rheology of debris flow, or the debris flow deposits in the context of fan stratigraphy and sedimentation or both. Excellent summaries of the former can be found in Johnson (1970), Owens (1973, 1975), Rodine and Johnson (1976), Takahashi (1981), Innes (1983), and Costa (1984). Studies of the sedimentology of debris flow deposits within the context of modern and ancient fans number in the hundreds; excellent overviews of these studies can be found in Nilsen (1982) and Bull (1972, 1977). Most studies of fan-related depositional processes have been carried out in arid and unglaciated mountainous regions (e.g. Blackwelder, 1928; Bull, 1964; Beaty, 1970). Studies, with application to this report, conducted in formerly glaciated areas in the North American Cordillera and other alpine regions have been chiefly concerned with the debris flow phenomena (e.g. Curry, 1966; Broscoe and Thompson, 1969; Owens, 1973; and Jackson, 1979) rather than fan geomorphology and sedimentology.

Studies of fans in areas that have been intensely glaciated, such as the Canadian Cordillera, are comparatively rare. Those that have been carried out have reached one or both of the following conclusions: 1) features traditionally referred to as alluvial fans are commonly in part constructed by debris flows and 2) fans predominantly constructed by debris flows may be relict features which have experienced little or no sedimentation and frequently have undergone extensive erosion over the past 6000 years (Winder, 1965; Ryder, 1971a, b; Church and Ryder, 1972; Roed and Wasylyk, 1973; Kostachuk et al., 1982).

Ryder (1971a, b) and Church and Ryder (1972) introduced the paraglacial concept to explain these observations. Paraglacial features, such as many of the fans in the Cordillera, formed rapidly following deglaciation when plentiful glacial drift remained in unstable settings, such as

Figure 4. Fresh debris flows on fans constructed by debris flow and avalanche activity, Selwyn Mountains, N.W.T., 1980. (A) View perpendicular to slope; grey areas are slightly older flows. (B) View parallel to slope illustrating the low slope angles traversed by the flows. ISPG 1958-17, 15.

Figure 5. Examples of stony debris flow deposits. (A) The unsorted matrix-supported structure is typical of debris flow deposits in the Canadian Rocky Mountains (Kananaskis Valley, Alberta). (B) The typical bouldery surface of a fresh debris flow, Kicking Horse Pass, British Columbia. ISPG 1958-13, 16.

the upper parts of mountain drainage basins. This material was particularly susceptible to debris flow due to the abundance of water from snowmelt, spring activity, melting of ground ice, and slope steepness. The resulting debris flows rapidly built fans at confluences between smaller tributary and larger trunk valleys. As supplies of debris waned, the growth of the fans decelerated until the transport of sediment from basin to fan reached an equilibrium, based on basin morphology, geology, and climate. In many cases the modern rate of sediment transport to the fans has been so low that their present streams have entrenched themselves across the full lengths of the fans. This is not to say that debris flow activity ceases in these basins. Debris flows which do occur may be largely confined within the basin and not reach the fan or are contained within the fan trench. The frequency of those that reach the fan surface may be low enough so that net erosion and incision of the fan prevails.

This paraglacial transition period between glacial and nonglacial denudational regimes has been documented over an entire drainage basin by Jackson et al. (1982).

PRESENT STUDY

Fans and their basins in three areas of the Canadian Rocky Mountains were investigated during the course of this study. These areas were chosen because they are representative of a wide range of terrain conditions found in the Rocky and Mackenzie mountains. Each area is described below and its location shown in Figure 6; Figures 7, 8, and 9 show the 103 fans and their basins investigated through field and/or airphoto study. Climatic summaries for the three areas are given in Table 1. The geology of the study areas is summarized in Table 2.

Kananaskis Valley/Spray Lakes Reservoir

This area is typical of extremely rugged areas of the Rocky and Mackenzie mountains which have been glaciated but no longer support glaciers other than small scattered cirque or niche glaciers. Adjacent drainages are usually separated by knife-edge divides and horn peaks. Mountain slopes are rugged and are commonly marked by avalanche tracks and talus cones. Relief, from valley floors to the summits to intervening divides, is up to 1500 m; maximum elevation exceeds 3000 m. Bedrock is composed of Paleozoic carbonates and Mesozoic clastics.

Elk River valley/Michel Creek valley

This area is representative of less rugged upland areas of the Rocky and Mackenzie mountains which were inundated by ice but generally were not centres of alpine glaciation with the exception of local cirque glaciers. Relief in this area rarely exceeds 760 m; elevations reach 2440 m but are generally less than 2130 m. Slopes are vegetated and are predominantly forested. Bedrock is mainly Mesozoic clastics. Avalanche tracks are restricted to the steepest slopes.

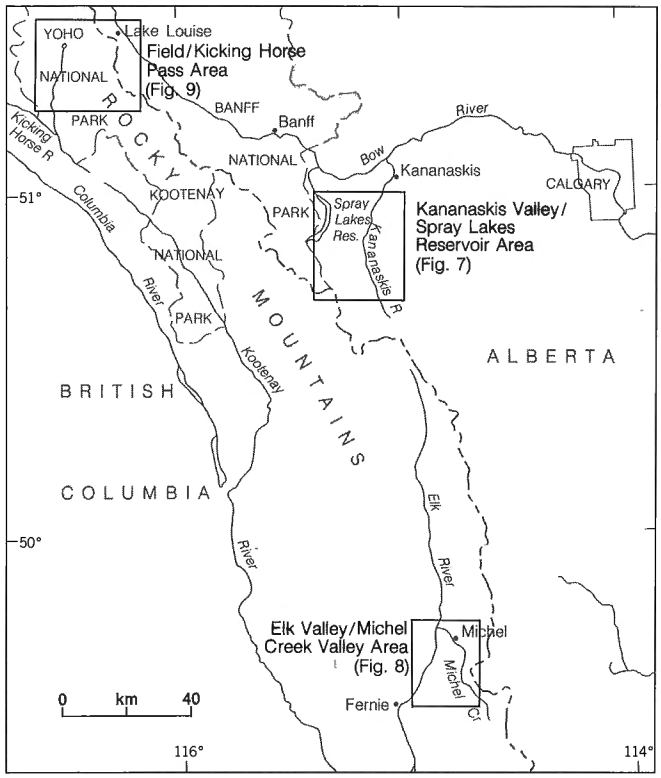


Figure 6. Location map showing the three study areas where fans were examined. Figures 7, 8, and 9 outline the individual basins.

Table 1. Summary of climatic data for stations within the areas studied for the period 1941-1970

Station (Study Area)	Daily Mean Temperature (°C) January	July	Mean Annual Precipitation (cm)	Rainfall (cm)	Maximum 24 h (Summer) Rainfall (cm)
Fernie, B.C. (Michel Creek valley/ Elk River valley)	-12.6	8.2	108.5	71.12	10.62
Kananaskis, Alberta (Kananaskis Valley/ Spray Lakes Reservoir	-16.0	6.1	67.74	37.69	8.20
Lake Louise, Alberta (Field/Kicking Horse Pass)	-21.4	3.4	76.76	28.50	5.26

Source: Environment Canada, 1973

Field/Kicking Horse Pass

This area is representative of rugged areas of the Rocky and Mackenzie mountains which support locally extensive mantles of glacial ice. Relief reaches 1680 m over distances of 2 km; maximum elevation exceeds 3050 m. The area includes large cirque glaciers and small ice caps including the Victoria, Cathedral, Stephen, Bath, and Emerald glaciers. Rock glaciers also abound in the area. The steep, glacially dissected topography has experienced almost all varieties of mass wasting phenomena from large catastrophic rockslides to local snow and rock avalanches. Recession of glaciers from their neoglacial maximum positions over the past 150 years (Luckman and Osborn, 1979) has left steep, ice-rich lateral and end moraines. Melting of ground ice and snowmelt on these features frequently triggers slumps and debris flows during the summer months. Glaciers in the area are known to catastrophically calve and also to release jokulhlaups (Jackson, 1979). Bedrock consists of lower Paleozoic and Precambrian quartzites and argillites.

INVESTIGATIVE METHODS

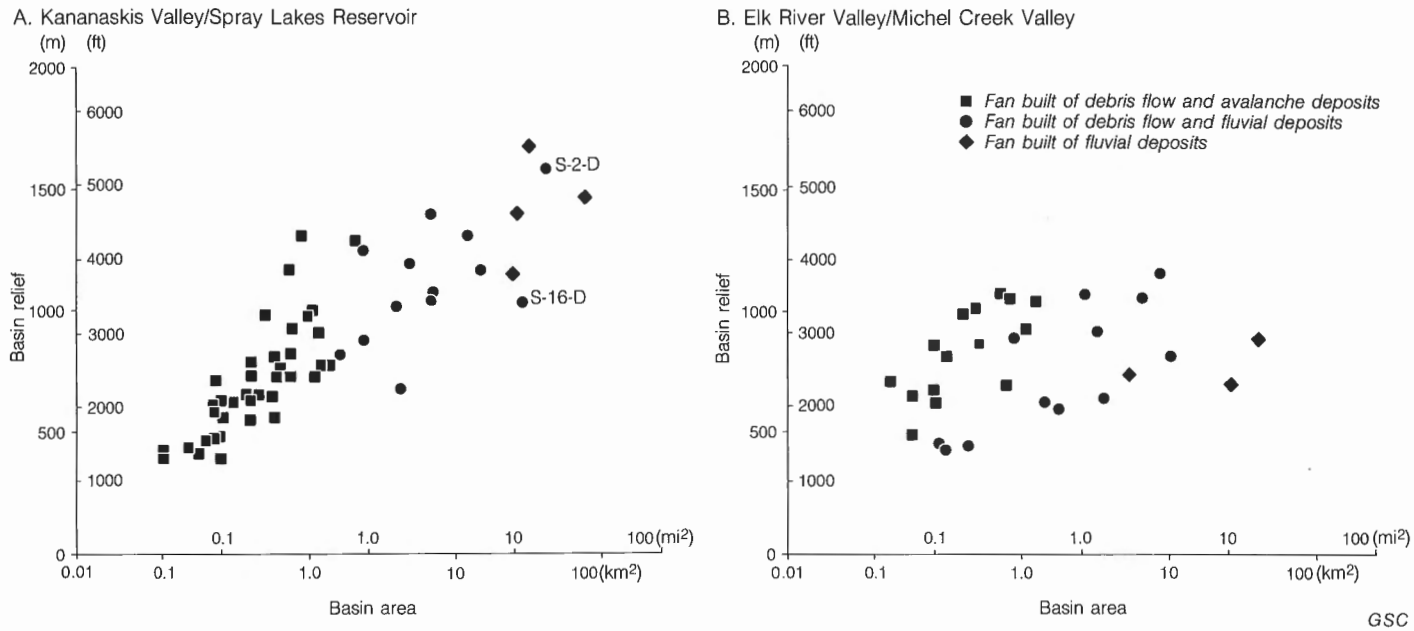
A total of 103 fans and their drainage basins were investigated through field or map and airphoto study. Of the 44 fans visited in the field, 21 were in the Kananaskis Valley/Spray Lakes Reservoir area, 14 were in the Elk River valley/Michel Creek valley area, and 9 were in the Field/Kicking Horse Pass area. All fans with natural or artificial exposures were examined to determine the presence or absence of debris flow sediments. Sediment samples of the <64 mm fraction of both debris flow and fluvial deposits were obtained for textural analysis at one or more sites on each fan, as exposures permitted. Sediment samples were analyzed as follows: the >2 mm ≤64 mm fraction was separated by screening. The weight per cent contents of the ≤2 mm (sand, silt, and clay) fraction were determined by hydrometer analysis. Where forest cover was sparse enough to permit, a tape and compass survey was made of each fan sampled to determine fan slope along a line as closely following the bisector of the fan as possible. Where this was

Table 2. Bedrock stratigraphy for the three areas studied (cf. Fig. 6)

Age	Formation[1]		Maximum Thickness (m)		Lithology[2]		Area of Occurrence[3] CN	KS	FK
Cretaceous	Belly River Formation		1200		ss/sh				
	Alberta Group		860		sh/ss				
	Blairmore Group		600		cong/ss/sh				
	Kootenay Group				ss/sh/coal/cong				
Jurassic	Fernie Formation		1030		sh/ss/coal/cong				
Triassic	Spray River Formation		540		ss/ds				
Upper Carboniferous	Rocky Mountain Group		360		ss/ds				
Lower Carboniferous	Rundle Group		540		ls/ds/ss				
	Banff Formation		270		sh/ls				
	Exshaw Formation		6		sh				
Devonian	Palliser Formation		242		ds/ls				
	Fairholme Group		670		ds				
Cambrian	Mistaya Fm.	McKay	120		ds				
	Bison Creek Fm.	Group	120	1970	sh	sh			
	Lyell Fm.	Ottertail Fm.	240	540	ds	ds			
	Sullivan Fm.		360		sh				
	Waterfowl Fm.		150		ds				
	Arctomys Fm.		150		sh				
	Pika Fm.	Chancellor Fm.	180	1360	ls	sh/ls			
	Eldon Fm.		300		ds				
	Stephen Fm.		90		sh				
	Cathedral Fm.		300		ds				
	Mount Whyte Fm.		90		sh				
	Gog Group		750		ss/cong				

Legend
ss-sandstone; sh-shale; cong-conglomerate; coal-coal; ls-limestone; ds-dolomite

[1] Vertical lines separates stratigraphically equivalent groups or formations and their respective thicknesses and lithologies.
[2] Lithologies shown in order of thickness.
[3] KS-Kananaskis Valley/Spray Lakes Reservoir area; FK-Field/Kicking Horse Pass area; CN-Elk River valley/Michel Creek valley area. After Gordy and Bruce (1962), Douglas et al. (1970), Ollerenshaw (1975). Vertical lines indicate the presence of a formation within the study area at the head of the column.



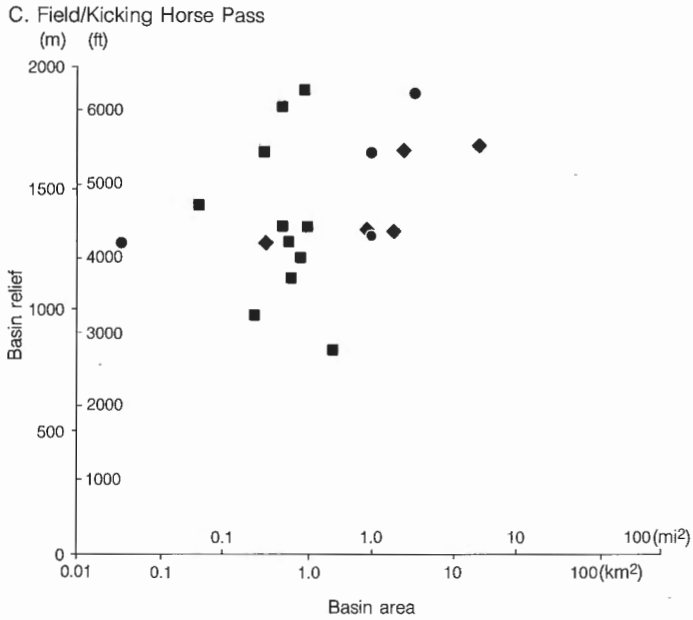


Figure 10

Basin relief versus basin area for the three study areas.

not possible, fan slopes were determined using 1:50 000 scale base maps. In addition, trees growing on debris flow deposits on the fans were cored to establish their ages and consequently the minimum ages of the debris flows beneath the trees. Living trees that were partly buried or injured by debris flows were felled to permit dating of the injury following the methodology described by Jackson (1975). The exposed fan stratigraphy was described at each site, including the presence and position of tephra (volcanic ash) layers and of organic material which could be dated by radiocarbon dating. These materials, when found in stratigraphic positions useful for dating past debris flow activity, were collected and dated. Fans that lacked exposures, but whose forest cover was sufficiently sparse to allow closely spaced traverses, were inspected for evidence of debris flow activity including levees, sinuous terraces formed by flow margins, and isolated boulders in excess of 0.5 m diameter.

The remaining 59 fans within the three study areas were studied through airphoto interpretation. Airphoto study indicated these fans to be subject to both avalanche and debris flow invasion. The bisector slope was determined using 1:50 000 scale topographic maps. The following morphometric parameters were determined for the drainage basins of all 103 fans studied, using 1:50 000 topographic maps: (1) relief between fan head and the highest point in a basin and (2) mean basin slope above the fan head and planimetric basin area.

STUDY RESULTS

An attempt was made to distinguish between fans built of both fluvial and debris flow sediments and those built purely by fluvial deposition on the basis of fan morphology, fan and basin morphometry, and texture of fan sediments. The results are discussed below.

Fan morphology

Fan slope appears to be useful in most cases in discriminating between exclusively fluvial fans and fans with a debris flow component. In all the 44 fans inspected in the field, no fluvial fan had an overall slope greater than 4° (e.g., Fig. 7 and 8, basins S-14-F and C-13-F). Debris flow fans, with only two exceptions (fans of basins S-2-D and S-16-D), have slopes greater than or equal to 4°. Fans with slopes greater than about 12° were found to have received snow avalanche – transported sediment in addition to debris flows, as has been previously noted by Luckman (1978).

Morphometry of drainage basins tributary to fans

Ryder (1971b) extensively described the relationship between basin and fan morphology for paraglacial fans in southern British Columbia. She showed a strong positive correlation between fan gradient and both relative relief number (the basin relief divided the square root of the basin area) and basin slope. She did not, however, directly examine the relationship between the presence of debris flows in fans and the morphometry of the parent basin. This was done for the three study areas (Fig. 10). In Figure 10 basin relief (the difference between the elevation of the highest point in the basin and the fan head) is compared to basin area. Short, steep basins (relief >500 m) with areas of less than 1-2 km^2 entirely or predominantly produce avalanche fans in all three areas, though some debris flow activity occurs (e.g., S-20-A, Fig. 7; C-14-A, Fig. 8). Lower relief basins (<500 m) in the Elk River valley/Michel Creek valley area, with areas of approximately 1 km^2 or less (Fig. 8), have produced mixed debris flow/fluvial fans (basins C-7-D, C-8-D, and C-9-D). The basin area and relief at which transition occurs from avalanche/debris flow fans to debris flow/fluvial fans to fluvial fans differ in the plots for the three study areas. In the Kananaskis Valley/Spray Lakes Reservoir and the Elk River valley/Michel Creek valley areas, debris flow/fluvial fans predominate for basins between about 2 km^2 and 10-12 km^2 in area. All fans occurring in larger basins in these two areas, with two exceptions, are entirely fluvial. The fans of the two basins S-2-D and S-16-D contain debris flow deposits; however, geomorphic evidence (fan head to fan toe stream entrenchment) and the lack of any organic deposits associated with the debris flow sediments suggest that these flows are very old – probably dating from deglaciation of the area as was previously noted. Consequently, these fans are paraglacial. Their basins must be considered as separate cases from the other basins represented in Figure 10. These two basins excepted, an abrupt transition from debris flow/fluvial to purely fluvial fans is apparent in Figures 10A and 10B. This transition is expected, because trunk streams of larger basins in a given region have greater mean channel widths and lower mean channel gradients than do smaller tributary basins (Leopold et al., 1964, p. 241-258). Beyond a certain basin area, these greater widths and lower gradients prevent debris flows generated in the upper basin from advancing as far as the basin mouth; this is because the flow becomes too thin as the channel widens and the gradient too gentle to permit flow to the fan head. An example is basin S-14-F (Evan Thomas Creek) in Figure 7. The fan of this basin is entirely fluvial. Debris flow/fluvial fans are present at the mouths of two sub-basins (S-18-D, S-3-D) within the Evan Thomas Creek basin. Sediment transport beyond these fans is entirely fluvial. The lack of discrimination between fluvial, debris flow/fluvial, and debris flow/avalanche basins in the Field-Kicking Horse Pass area (Fig. 9) results from local sediment traps which retain debris flows and avalanches above fan heads (e.g., Larch Valley is a sediment trap in basin L-20-F, as is the bench above Ross Lake, in basin L-22-F). These permit some smaller drainage basins to have entirely fluvial fans, whereas fans of basins of similar size in the Kananaskis Valley/Spray Lakes Reservoir area without these traps would likely be built partly of debris flows.

The widespread occurrence of low gradient valley segments (steps) within the overall rugged topography of the Field/Kicking Horse Pass area is characteristic of the Rocky Mountain Main Ranges. This step-like topography is the result of glacial erosion of the flat to gently dipping rocks of the Main Ranges.

Texture of fan sediments

Fluvial sorting processes are not involved in the transportation and deposition of diamictons, such as debris flow deposits, although postdepositional fluvial reworking of debris flows may occur. The presence of very coarse clasts set within a matrix containing abundant silt and clay is one of the principal criteria used to distinguish debris flow deposits from fluvial deposits in the field. Bull (1962) used this lack of sorting as a diagnostic tool for distinguishing between poorly sorted sediments of fluvial flow and those of high density flow (debris flow, mudflow) origin. He plotted the largest one-percentile against the median grain size. This approach effectively separated fluvial and debris flow deposits into distinct areas on the diagram.

This method, while effective, has the disadvantage of requiring a complete textural analysis. A slightly modified version of Bull's plot was successfully applied to textural data determined on sediment samples collected from the fans in the three areas studied. The weight per cent content of the >2 mm $\leq$64 mm fraction was plotted against weight per cent clay content for these samples. Figure 11, line 1, marks the break between sediments of known fluvial origin and of debris flow origins. Sediments with mixed characteristics, as noted in the field, that is poorly sorted but partly stratified, appear to be predominantly of fluvial origin based upon this plot. This procedure has the advantage of requiring a simple screening of the sample into coarse and fine fractions and the determination of the clay content by the rapid hydrometer method.

Published textural data for debris flow sediments and related fluvial sediments from elsewhere in the Canadian Cordillera plot within the same area of the gravel-clay plot as the sediments sampled during the course of this study. For example Figure 12 shows Ryder's (1971a) textural data for alluvial fan sediments from across the southern interior of British Columbia. While she did not state clearly which samples were debris flow and which were fluvial or intermediate in origin, she did indicate that most were obtained from debris flows.

Line 2 of Figure 11 separates fluvial and debris flow textural data taken from Bull's (1964) study of fans in southern California. This second line appears to indicate that this method works as well for debris flows in sediments in nonglaciated areas as in glaciated ones. The wide divergence between the data in the two plots probably reflects the difference in rock types and erosional and weathering environments responsible for producing the sediments transported by debris flow in the two areas.

METHODOLOGY FOR EVALUATING DEBRIS FLOW HAZARD ON FANS

With the previous discussion as reference, a methodology for determining debris flow hazard on fans in the Rocky Mountains, and geologically similar upland areas is suggested. The procedure seeks first to establish whether debris flows have at least partly constructed the fan under

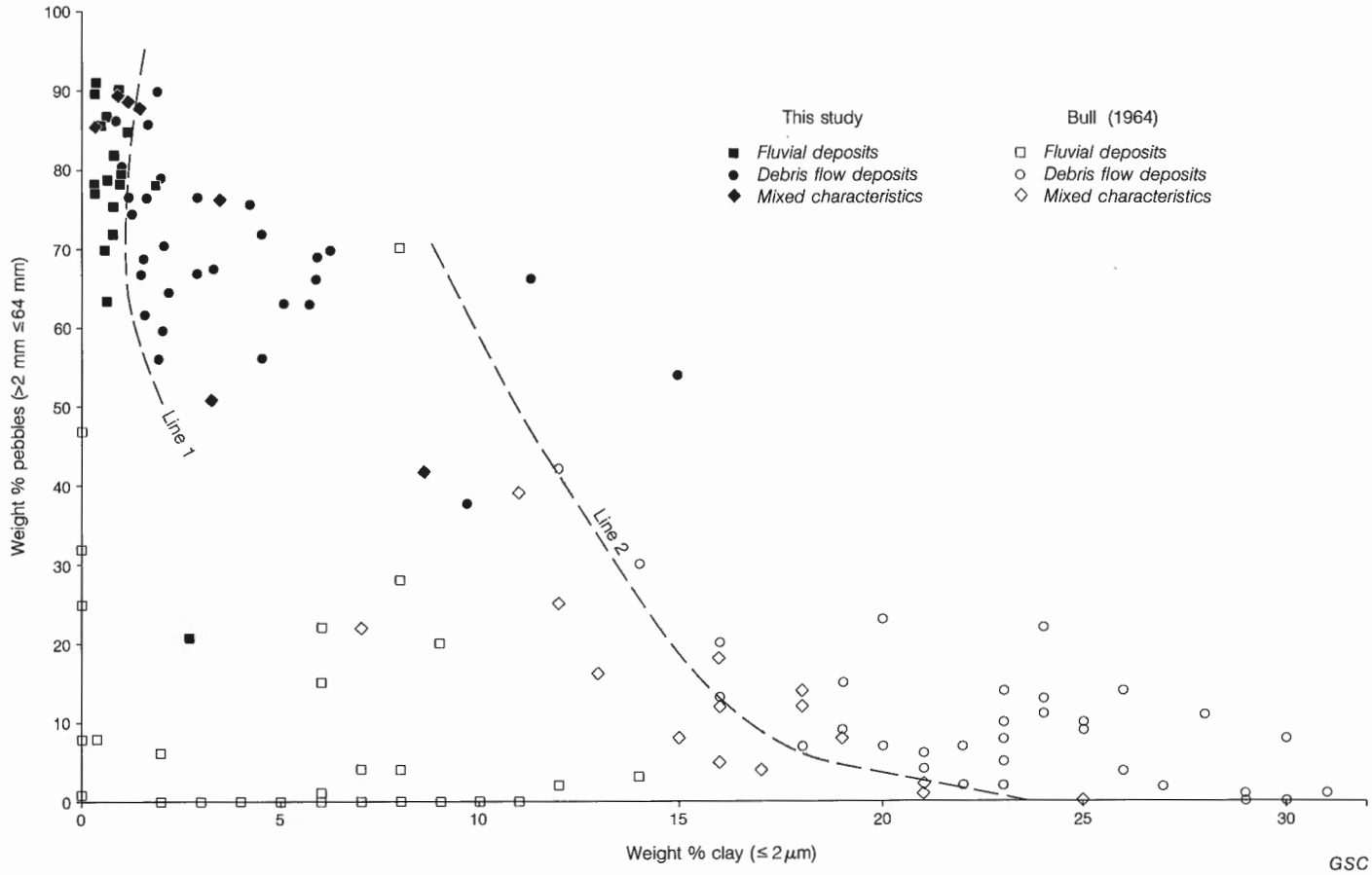


Figure 11. Clay content (≤ 2 μm) versus pebble content (> 2 mm ≤ 64 mm) for samples collected during the course of this study and by Bull (1964). The lines separate fields of values for debris flow samples from those for fluvial samples (see text for explanation).

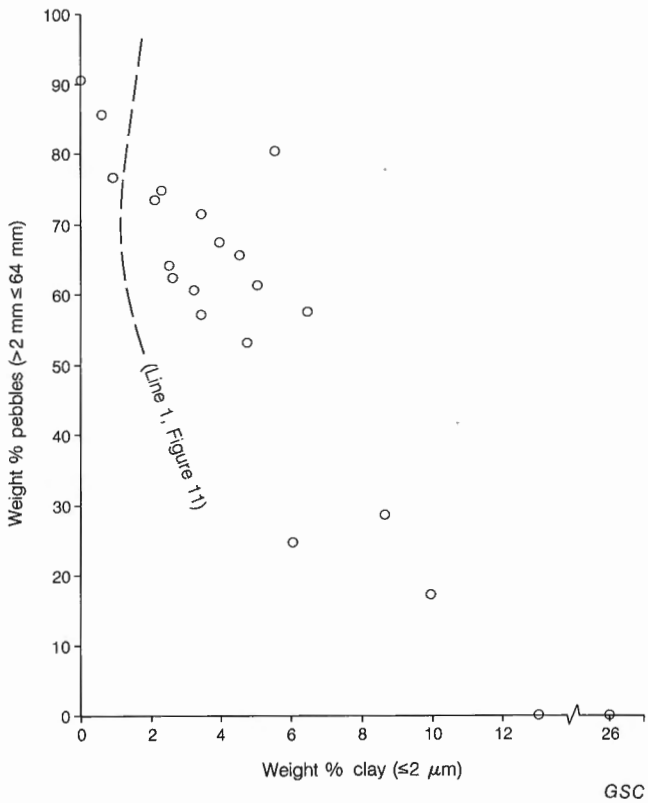


Figure 12. Clay content (≤ 2 μm) versus pebble content (> 2 mm ≤ 64 mm) for debris flows and related sediments collected by Ryder (1971a) from fans in the southern interior of British Columbia. Line 1 is reproduced from Figure 11.

study and, if so, to establish past debris flow frequency so that planning and engineering decisions can be made with respect to whether or not development should proceed and what protective or mitigating structures should be built. This methodology is described in the following sections and summarized in Figure 13.

Establishment of the occurrence of past debris flows

Evidence from sediment texture, fan morphology, and basin morphometry and geomorphology can be used to establish past debris flow activity on a fan. Each of these lines of evidence may be subdivided into individual criteria which are suggestive, highly suggestive, or conclusive evidence of past debris flow activity. It should be kept in mind that only the absence of all of these criteria in a fan can be taken as proof of an absence of past debris flow activity.

Textural evidence

Any of the following is conclusive evidence of the past occurrence of debris flows on a fan:

1. the recognition of a stony, matrix-supported diamicton in natural or artificial exposures within a fan;
2. textural data from a fan plotting to the right of line 1 on Figure 11; and
3. where no exposures are present, large (>0.5 m) isolated boulders resting on the fan surface[1].

Evidence from fan morphology

Either of the following is conclusive evidence of past debris flow activity:

1. steep sided levees, similar to those shown in Figure 14, along active or abandoned stream courses; and
2. debris flow lobe margins; these are apparent as sinuous terraces which are studded with boulders along their margins.

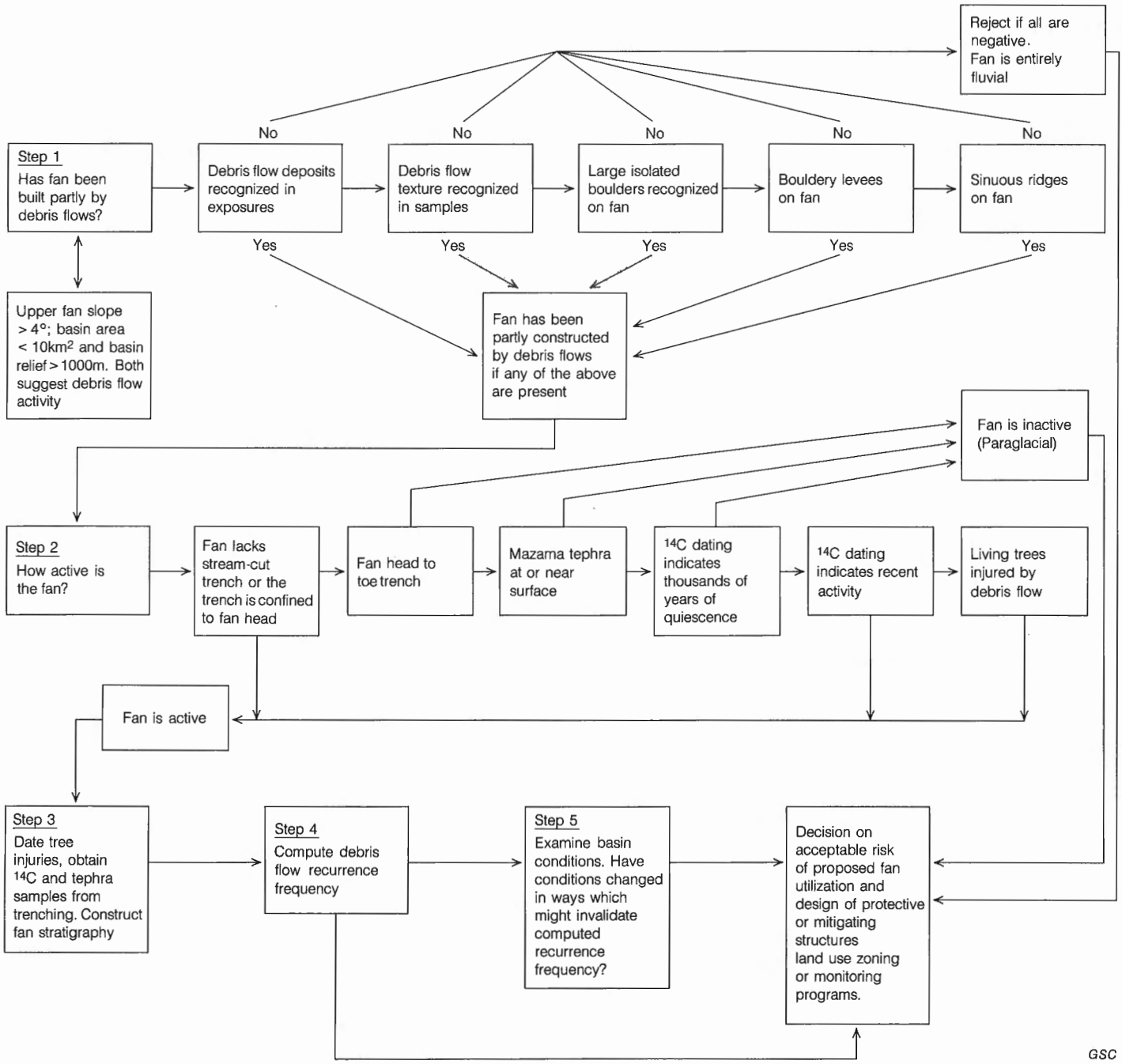


Figure 13. A flow diagram summarizing debris flow hazard evaluation methodology discussed in this report.

[1] Extensive deposits of very large boulders with gravelly matrixes, such as those described by Bradley and Mears (1980) and Costa and Jarrett (1981), may indicate past torrential floods rather than debris flows.

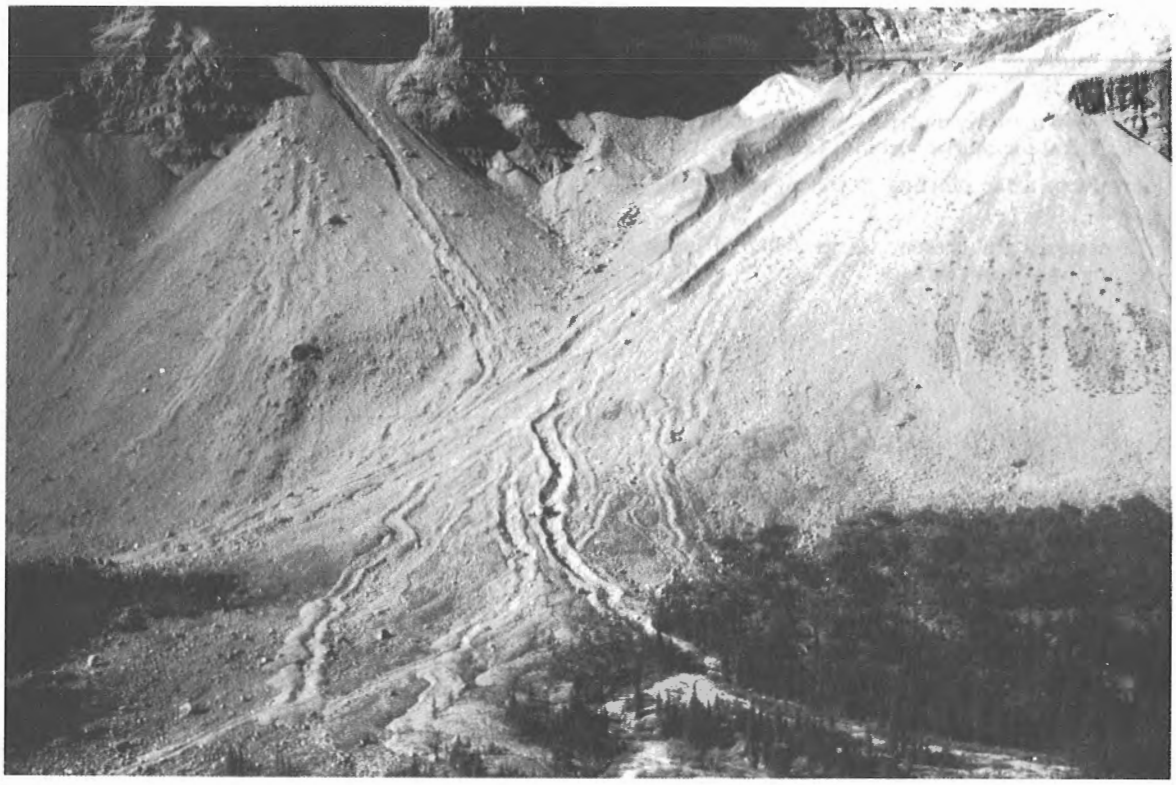


Figure 14. Levees on a fan built by debris flows triggered by ground-ice thaw in adjacent neoglacial moraines along the Banff-Jasper Highway, Alberta. ISPG 1958-1.

Table 3. Summary of widespread Holocene tephras in the Canadian Cordillera [1,2]

Tephra	Age of deposition	Age reference	Comments
White River	western lobe 1850-1900 BP; eastern lobe ca. 1220 BP	Hughes et al., 1972	No other Holocene tephra has been found within the region. For analytical data see Lerbekmo and Campbell (1969); for distribution see Bostock (1952, p. 36-39).
Bridge River	two tephras from eruptions ca. 2000 and ca. 2600 BP	Westgate, 1977	Identification based on inclusions in plagioclase, accessory mineral suite, and magnetite chemistry.
St. Helens Y	ca. 3400-4300 BP	Westgate, 1977	Two tephras so close in composition as to be indistinguishable. Identified by glass and magnetite chemistry.
Mazama	ca. 6600 BP	Westgate et al., 1970	Identification by refractive index of glass, accessory minerals, and glass chemistry.
Glacier Peak	ca. 12 000-13 000 BP	Fryxell, 1965; Ives et al., 1967	Identification based on glass chemistry. Possibly two tephras from the same source.

[1] Geographic distribution shown in Figure 15.
[2] The St. Helens P tephra has been tentatively identified by Westgate (1977); its distribution in the Canadian Cordillera has yet to be established.

Fan slope angles of >4° should be regarded as highly suggestive evidence of past debris flow activity. The degree of certainty increases with increasing fan slope. Fans with slopes >12° may have experienced past avalanche activity as well.

Evidence from basin morphometry and geomorphology

Basin morphometry can provide suggestive or supporting evidence for past debris flow activity on a fan. Basin morphometry is not in itself a source of conclusive evidence. Supporting morphometric evidence includes:

1. basin areas of less than 10-12 km^2 and internal relief of more than 500 m;
2. the presence of sub-basins with the above dimensions which are tributary to the trunk stream of a larger basin at or immediately above the head of the fan constructed by the larger stream;
3. basins which are likely to experience large, sudden releases of water from sources such as jokulhlaups or related events such as the failure of moraine-dammed lakes or temporary damming by landslides; and
4. basins with dimensions as in (1) above, and containing fresh, ice-cored moraines.

The importance of recognizing (3) and (4) can be illustrated with examples drawn from Figure 9. Basins B-1-A, L-15-D, and L-21-D all have fresh, active debris flow fans. Debris has been largely derived from ice-cored moraines built by an advance which terminated within the past 150 years. The fan of basin B-1-A shows evidence of a recent release of large volumes of water, possibly from a moraine-dammed lake. Basin L-21-D has had a record of jökulhlaups and attendant debris flows throughout this century (Jackson, 1979). In contrast, the fan of basin G-13-F shows no evidence of past debris flow activity even though glacial recession has stranded large volumes of unstable morainal material in the upper basin. Although no debris flows have apparently reached this active fluvial fan, there is every likelihood of future debris flow activity based upon the experience of comparable basins in the area.

Evaluation of debris flow hazard

Once a fan has been identified as being at least partly constructed of debris flow deposits, the past frequency of debris flow activity must be established in order for a measure of risk to be assigned to the desired activity proposed for the fan. Where debris flow activity has been historically documented (for example Jackson, 1979) this is a relatively simple process. The number of debris flows over the period of record permits an estimate of the number of

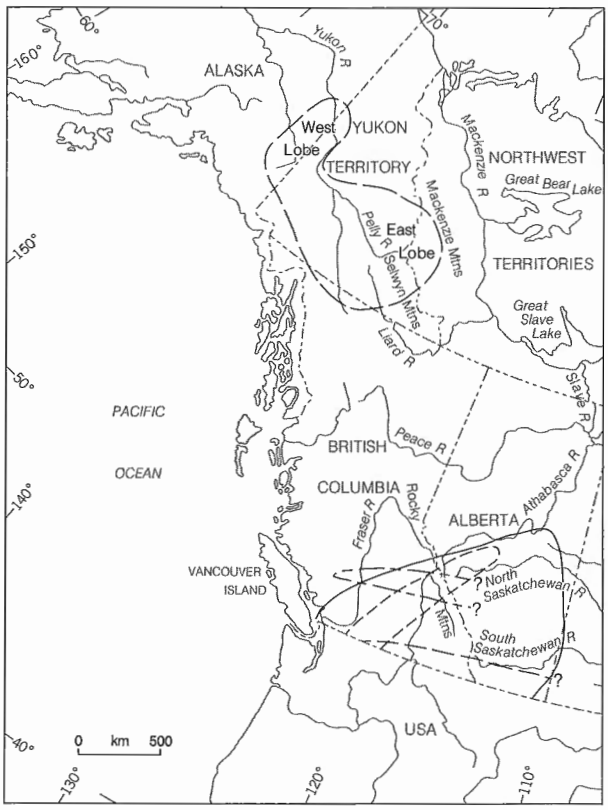


Figure 15. Distribution of Holocene tephras in the Canadian Cordillera.

Figure 16. Mazama tephra (dashed line) near the surface of a partly dissected paraglacial fan, Kananaskis Valley, Alberta. The dotted line marks the top of the most recent debris flow deposit exposed in this part of the fan. ISPG 1629-7.

years between debris flow episodes. For the Rocky Mountains and other northern upland areas, historical records of such events are rare. Furthermore, as described earlier, many fans are paraglacial and are no longer growing but rather are being slowly dissected. Consequently, these latter fans provide low hazard building sites. Their identification is highly desirable.

Identification of inactive or nearly inactive debris flow fans

Identification of fans which are paraglacial depends upon the presence of: 1) datable horizons within the fan and 2) geomorphological evidence indicating long term quiescence on the fan surface.

Datable horizons are usually restricted to fluvial or debris flow sediments containing entrained organic material suitable for radiocarbon dating; actual buried, organic-rich horizons such as soils and root layers; and tephra layers. In paraglacial fans, organic materials are usually lacking because most of the debris flow activity apparently predated forested conditions (Jackson et al., 1982). Consequently, tephra layers, where they occur, have proved useful in establishing the inactivity of fan surfaces. Four tephras or closely related groups of tephras have been identified in the southern Rocky Mountains and elsewhere in the southern Cordillera; one widespread tephra is present in the Yukon River basin (Fig. 15). Details of these tephras are summarized in Table 3. Of these five, the Mazama has proven to be the most valuable in identifying paraglacial fans due to its age and wide distribution. It is typically within 1 m of the fan surface (Fig. 16) and thus indicates minimal depositional activity during the past 6600 years. The other tephras are also useful but, with the exception of the Glacier Peak tephra, are indicative of substantially shorter periods of nondeposition. The Glacier Peak tephra has a very limited extent within the Canadian Cordillera which limits its usefulness.

Where tephra horizons and radiocarbon-datable material are lacking, geomorphological evidence must be employed. The chief geomorphological criterion to consider is the depth and extent of fan incision. The heads of fans deposited by both both debris flow and fluvial sedimentation are frequently incised. Hooke (1967, p. 451) attributed this to the "high viscosity and finite yield strength" of debris flows. Because of this "...the hydraulic gradient required for their movement is greater than that required by water for transport of much of the finer material in them. Consequently water flows tend to erode channels in debris flow deposits...". On active alluvial fans, however, incision is restricted to the fan head. Material eroded from the fan head is redeposited farther down the fan. In the case of paraglacial fans, such as those described by Jackson et al. (1982), the trunk streams have incised themselves into their former floodplains, that is, below the level to which the fan was previously graded. The results are an entrenchment of the fan stream over the entire length of the fan and a truncation of the toe by the trunk stream (Fig. 17). These types of fans can be considered safe sites for such activities as urban or recreational development because debris flows and high water flows are naturally channellized. As an added precaution, however, maximum instantaneous discharge calculations should be made for the basin in order to verify that the incised channel is capable of handling floods with long recurrence intervals.

Figure 17. Airphoto of paraglacial fans showing characteristic fan head to toe incision (indicated by arrows) and truncation of the fan by the trunk stream (Kananaskis River). ISPG 1958-18.

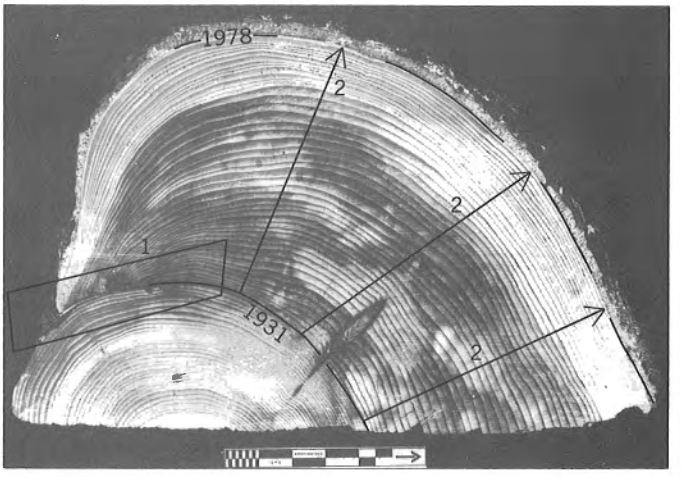


Figure 18. A section of a tree trunk, injured on its upslope side by a large boulder carried by a debris flow, showing (1) the injury and callous growth around the injury and (2) buttress growth. The age of the tree in 1979 was 92 years. The debris flow and injury occurred ca. 1931 (Evan Thomas Creek basin, Kananaskis Valley, Alberta). ISPG 1985-19.

Establishment of debris flow frequency on active fans

Several techniques are available for establishing debris flow frequency on active fans. All seek to provide the year of the last debris flow and/or bracket flow occurrences in time, with minimum and maximum ages. In forested areas, trees may yield excellent records of debris flow activity. Debris flows often abrade or otherwise injure trees on their up-fan sides. If no subsequent flows injure the tree, these scars eventually heal by peripheral or callous growth around the scar. This scar growth is apparent when viewed in a cut section (Fig. 18). The year of the injury can be closely approximated by dating the first annual growth ring on the outside of the scar (Sigafoos, 1964). When a tree is tilted by the force of a debris flow, buttress growth results. Buttresses are identified by unusually wide growth rings in the direction of tilt (Fritz, 1934). The buttress mechanically compensates for the tree's unbalanced weight distribution. The age of initiation of buttress growth will closely date the debris flow. A detailed account of the application of tree injuries to the dating of inundative events is presented by Sigafoos (1964).

For fans on which the most recent debris flow predates the oldest living tree on the fan, the age of the oldest living tree on the debris flow deposit will provide a minimum age for the flow (Fig. 19A)[1]. Lichenometry may be used on alpine or northern fans beyond the timber and tree lines, respectively (Osborn and Taylor, 1975; Luckman and Osborn, 1979). This method, however, was found to be unsatisfactory within forested areas because lichens are destroyed by forest fires. Lichens were always found to date closely the last forest fire rather than the last debris flow which, based on the ages of the oldest trees growing nearby or on radiocarbon dating, was much older.

Figure 19

(A) Stump of a recently logged tree which was growing on the surface of the most recent debris flow on a fan in the Michel Creek basin, British Columbia. The age of the tree when felled (ca. 1978) was 271 years. (B) Patterned band indicates a charcoal-rich horizon, beneath the same debris flow, which was dated at 2530 ± 90 BP (GSC-3047). These data indicate that only one debris flow occurred on this fan between 2500 years and 272 years ago. ISPG 1958-3, 5.

[1] The oldest dead standing tree can be used if its annual ring pattern can be cross-dated to living trees. See Fritts (1971) for an introduction to the methods of dendrochronology.

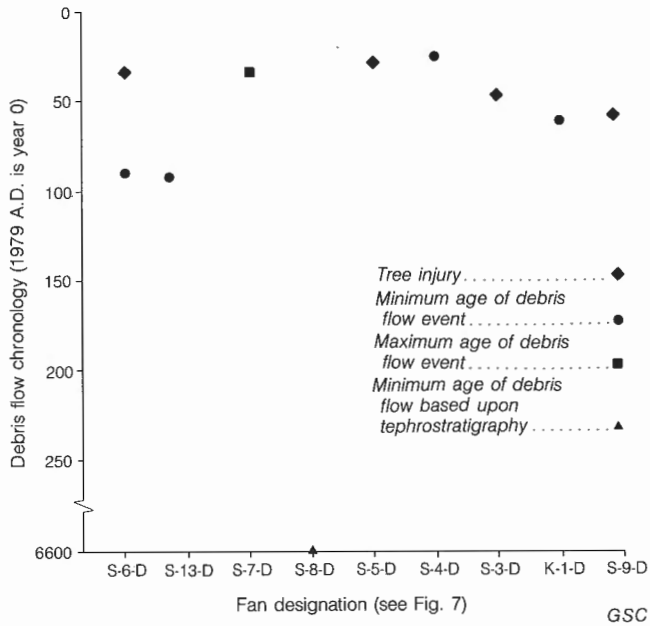


Figure 20. Debris flow chronology determined for nine fans in the Kananaskis and Spray Lakes valleys.

Maximum ages for debris flows that predate the present forest cover can only be determined using radiocarbon dating or tephrostratigraphy. Natural and artificial excavations in the fan must be inspected in order to obtain datable materials (Fig. 19B). Debris flows in forested areas invariably entrain woody material and spill out onto forest floors, burying soils and root horizons.

Establishment of minimum and maximum ages for debris flows in a fan provides a frequency of past debris flow activity. This frequency should be considered a minimum estimate. It is always possible that more debris flows occurred without leaving a discernible record. It should also be kept in mind that the record of past debris flows usually reflects undisturbed conditions. Road construction, logging, and grazing, to name only three man-induced disruptive land-use activities, may radically alter the natural erosional regime in a basin and significantly increase the frequency of debris flow occurrence. Changes in glacial activity within a basin such as ice-front retreat which leaves ice-cored moraines, is a natural modification that can have the same result.

APPLICATION OF THE METHODOLOGY – KANANASKIS RIVER AND SPRAY LAKES VALLEY

Determination of the past frequency of debris flow on a fan should ideally incorporate a three dimensional view of fan stratigraphy. This necessarily involves trenching across the fan surface so that radiocarbon-datable horizons beneath flows and intervening fluvial sediments can be better established. Natural exposures on fans, with rare exceptions (e.g., Jackson, 1975), usually permit dating of only the most recent debris flow event. Of the three areas studied, only the Kananaskis and Spray Lakes valleys (Fig. 7) yielded sufficiently unequivocal data to be reported here. In the Elk River/Michel Creek valley area (Fig. 8), extensive fires in the 1930s destroyed much of the forest cover. Consequently, the oldest trees on the fans usually dated to those events. Only where artificial cuts were present could any significant information on past debris flow activity be obtained (Fig. 19). The Field/Kicking Horse Pass area straddles Banff and Yoho National parks. The felling of trees, which is necessary for dating of flows, was not permitted.

In the Kananaskis and Spray Lakes valleys, nine fans yielded significant chronological data on the most recent debris flows. Only one of these fans yielded information on an older event.

These two valleys were virtually uninhabited until about 1950. No reports of debris flow activity were available from existing historical records. The chronology of debris flows on these fans, based upon the previously outlined methodology, is summarized in Figure 20 and the fan locations are shown in Figure 7. Seven out of the nine fans have experienced debris flows during the last 60 years. Of the others, fan S-8-D is clearly paraglacial with no evidence of debris flow activity since before the deposition of the Mazama tephra. The fan is crossed by a deeply incised head-to-toe trench. Fan S-13-D has not experienced a debris flow in more than 92 years – the age of the oldest tree now growing on the fan. Without trenching, the past recurrence frequency over a reasonable period of time – perhaps 500 or 1000 years – is not available. However, this chronology shows debris flow has been active on many fans in the valley under pristine watershed conditions and should be taken into account in any land use planning for these sites.

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