CHAPTER 17

Hazard Management on Fans, with Examples from British Columbia

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Abstract

Considerable development has occurred on alluvial fans in British Columbia because they often are the only gently sloping sites available. They also tend to appear deceptively safe because the two main hazards—channel avulsions and debris-flows—are highly intermittent and their traces disappear under dense vegetation after a few years. A sequence of events within the last decade has prompted several studies of fan hazards. Because of their destructive nature, clear identification of any potential for debris-flows to reach a fan is the key element of hazard assessment.

A hazard zoning system has been developed to deal with both fluvial avulsions and debris-flows. Mitigating measures implemented so far differ significantly from those commonly used in the European Alps or in Japan. Channelization and riprap-lined dykes are the most common measures because of the relatively low costs of land and earth moving. Warning devices, debris chutes, and debris interception barriers with debris-straining outlet structures have also been built. Upstream slope and channel stabilization is not usually feasible.

Introduction

The British Columbia land area of some 923 000 km^2 is made up primarily of mountains and dissected plateaus. While most human settlement is confined to large river valleys, to the coastal plain of the Strait of Georgia, and to the province's small share of the Northern Great Plains, important communication links such as railways, highways, pipelines, and transmission lines cross high mountain ranges. Many small towns with economic bases in forestry, mining, tourism, or communication are also located in mountainous terrain or along the steep, fjord coast.

As in many other mountainous areas, and particularly in lake or fjord-filled valleys, fans are often the only gently sloping surfaces below ridge top levels. To the untrained eye these fans may look like the most suitable sites for a wide variety of developments ranging from farming to housing, industrial facilities, or transportation routes.

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Needless to say, first impressions often deceive and fan surfaces are increasingly being recognized as potentially very hazardous. The indiscriminate development of fans has already led to considerable economic losses and loss of life.

Hazard problems associated with fans are not nearly as serious in British Columbia as in other mountainous areas with a long history of human settlement such as Japan (Erosion Control Engineering Society of Japan, 1985) or the European Alps (Eisbcher and Clague, 1984). Nonetheless, there are many situations in the province where alternate sites away from fans simply are not available, or where moving activities to an alternate site is not a reasonable option due to the level of existing developments. The degree of hazard on fans also varies widely from fan to fan and between different areas on any particular fan. Clearly, then, simple avoidance of the hazards associated with developments on fan surfaces is only one of several approaches that need to be considered. Procedures are required to classify, rank, and map the degree of hazard on fan surfaces and protective measures are needed for developments otherwise exposed to excessive hazards.

This paper addresses the general nature of hazards associated with developments on fans and describes field and office procedures developed in British Columbia for their identification and assessment. Finally, the two basic remedial options, avoidance through hazard zoning and construction of protective works, are discussed and illustrated with recent examples.

Both truly alluvial fans that have been built by fluvial sediment transport and deposition, and fans that are partially or entirely the result of debris-flow deposition are considered. Small, steep fans consisting primarily of debris-flow deposits are also known as debris cones.

Nature of Hazards

STREAM AVULSION

Fans are aggradational, fluvial features of the landscape and, as in the case of related features such as deltas, streams on fans are subject to avulsions; that is, sudden, often drastic shifts in channel position (Figure 17.1). Active alluvial fans are gradually being built up through the deposition of parts of the coarse sediment load of a stream. This deposition tends to take place in or near the stream channel with the result that the stream eventually flows at the top of a gentle ridge across the fan. During a major flood it tends to break out of its channel to find itself a new, more stable location. The exact route of the new stream channel is often quite unpredictable. It may be determined by a series of random events such as debris jams, or plugging of culverts and bridges. A very minor depression in the fan surface, such as a road ditch, can suddenly become a major stream course.

In contrast, 'sheetfloods'—laterally extensive, shallow flows—occur mainly on the distal parts of alluvial fans in deserts, where truly torrential downpours flow out onto surfaces with little or no vegetation and very attenuated relief. Even here, flows shift unpredictably.

Avulsions do not constitute 'flooding' in the classical sense of the word and the hazards associated with exposure to avulsions are not readily dealt with on the basis of floodplain mapping. Since fan surfaces are, by definition, unconfined, the normal backwater profile computational procedures of floodplain mapping are simply inapplicable, although this has not deterred many agencies from applying them. Many floodplain maps of fans have been published that give a mistaken impression of a 'normal' flooding hazard involving mainly inundation, when in fact the real hazard is related to potential avulsions. Avulsions normally are associated with high current velocities, erosion, and sediment deposition, including very coarse debris. In almost all instances avulsions are a much more severe hazard than normal 'flooding'.

As soon as the flood flows exceed the capacity of the stream channel on a fan the location, extent, and depth of flooding tend to become highly unpredictable. Since fan surfaces normally slope away from the stream in all directions and are often quite irregular on a microscale, with many old stream channel traces, the overflow is

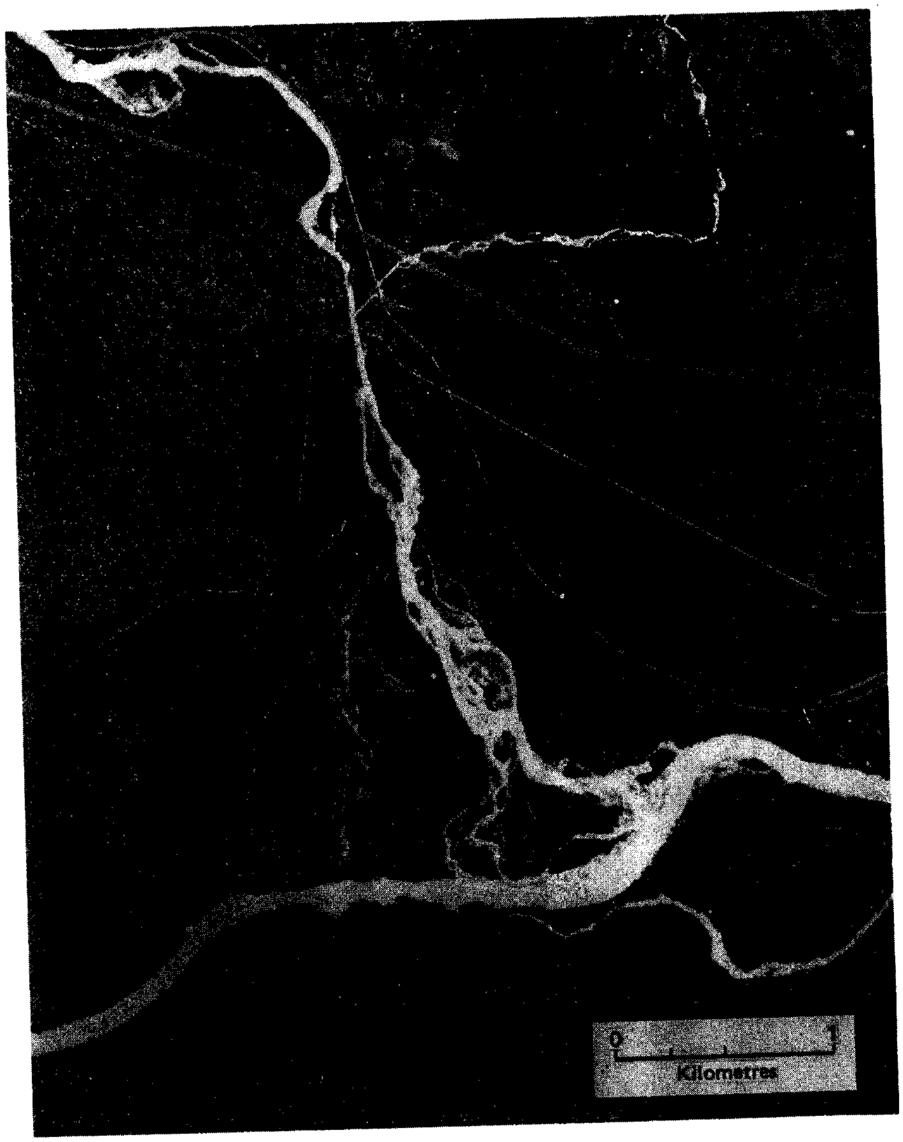


Figure 17.1. Modern alluvial fan of Cheakamus River, tributary to Squamish River near Squamish, British Columbia. Recent courses of the river are identified by immature and incomplete vegetation development (arrows). The stream moved suddenly to its present course by avulsion

likely to be concentrated into one or several channels. Initially this will be mainly water skimmed off the top of the existing channel, while the coarse bed material load will continue to move on down the channel. The loss of discharge immediately reduces its carrying capacity and this often results in rapid, complete plugging. The new outflow stream is likely to have a relatively steep slope, little coarse sediment, and therefore much erosive power. All of this tends to accelerate avulsions once they are initiated.

DEBRIS-FLOW

Steeper fans can also be exposed to various hazards associated with debris-flow processes. A debris-flow is a slurry of water and sediment, with possible addition of organic debris, avalanching down a steep slope or a steep, confined channel. These flows contain such a high percentage of solids that their mechanics differ greatly from normal, turbulent, open-channel flow of water (see Costa, 1984, for extensive descriptions). Since the hazards posed by debris-flows are different and generally far more serious than those associated with the above-described 'normal' alluvial fan processes, it is important to identify any potential for debris-flow to occur.

Debris-flow includes a considerable range of related flow phenomena, depending on the concentration and size distribution of the included solid material. Flows containing mainly cohesive fines (i.e. clay and silt) are normally referred to as mud flows. They are characterized by relatively slow motion and by their ability to maintain motion on remarkably low gradients of just a few per cent. The term 'debris-flow' normally refers to flowing mixtures containing a much wider range of grain sizes, extending to boulders (Figures 17.2A, B).

'Debris torrents', a term used mainly in British Columbia and in the adjacent Pacific Northwest of the United States, occupy the other end of the spectrum: they tend to contain very little solid material below sand size and to consist primarily of gravel to boulder sized material, with often a large percentage of organics ranging in size from mulch to logs and root boles of large trees (Figures 17.2B, C). Swanston and Swanson (1976) described debris torrents as follows:

> Debris torrents typically occur in steep, intermittent, first- and second-order channels. These events are triggered during extreme discharge events by slides from adjacent hill slopes which enter a channel and move directly downstream, or by a breakup and mobilization of debris accumulations in the channel. The initial slurry of water and associated debris commonly entrains large quantities of additional inorganic and living and dead organic material from the streambed and banks. Some torrents are triggered by debris avalanches of less than 100 m^3, but ultimately involve 10 000 m^3 of debris entrained along the track of the torrent. As the torrent moves downstream, hundreds of metres of channel may be scoured to bedrock. When a torrent loses momentum, there is deposition of a tangled mass of large organic debris in a matrix of sediment and fine organic material covering areas up to several hectares.

Several events involving more than 50 000 m^3 have been observed in British Columbia, and the largest documented event—in a wilderness area—is of the order one million cubic metres (Clague *et al.*, 1985).

Most British Columbia mountains are characterized by resistant bedrock, thin or absent veneers of unconsolidated materials, dense forest cover, and steep slopes, all of which lead to a predominance of true debris torrents made up of very coarse material requiring steep, well-confined channels to maintain motion (Figure 17.2B). In heavily forested areas, the proportion of organic material can approach or exceed 50% by volume (*cf.* Figure 17.2C). Areas characterized by deep veneers of unstable, weathered, or unconsolidated materials, sparse or absent vegetation cover, and generally unstable slopes occur primarily in northern British Columbia and in the Rocky Mountains. They tend to produce debris-flows containing finer material and capable of travelling on lower gradients (Figure 17.2). True mud flows, consisting entirely of flowing cohesive material, are not normally associated with alluvial fans because source areas of fans tend to yield coarser material.

In a discussion of the practical aspects of dealing with debris-flows, Hungr *et al.* (1984) described the debris-flow process observed in British Columbia as follows:

> Many debris-flow events occur in two or more surges, spaced over several hours. Individual surges have short durations measured only in minutes, and are commonly associated with abundant water flooding. A typical surge through the lower reaches of a mountain creek begins by the rapid passage of a steep bouldery front, followed by the main body of the flow. This consists of unsorted coarse particles ranging from gravel to boulders and logs, floating in a slurry of liquified sand and finer material. Both the proportion of fines and the water content increase in the later stages of the surge, forming a liquid 'after

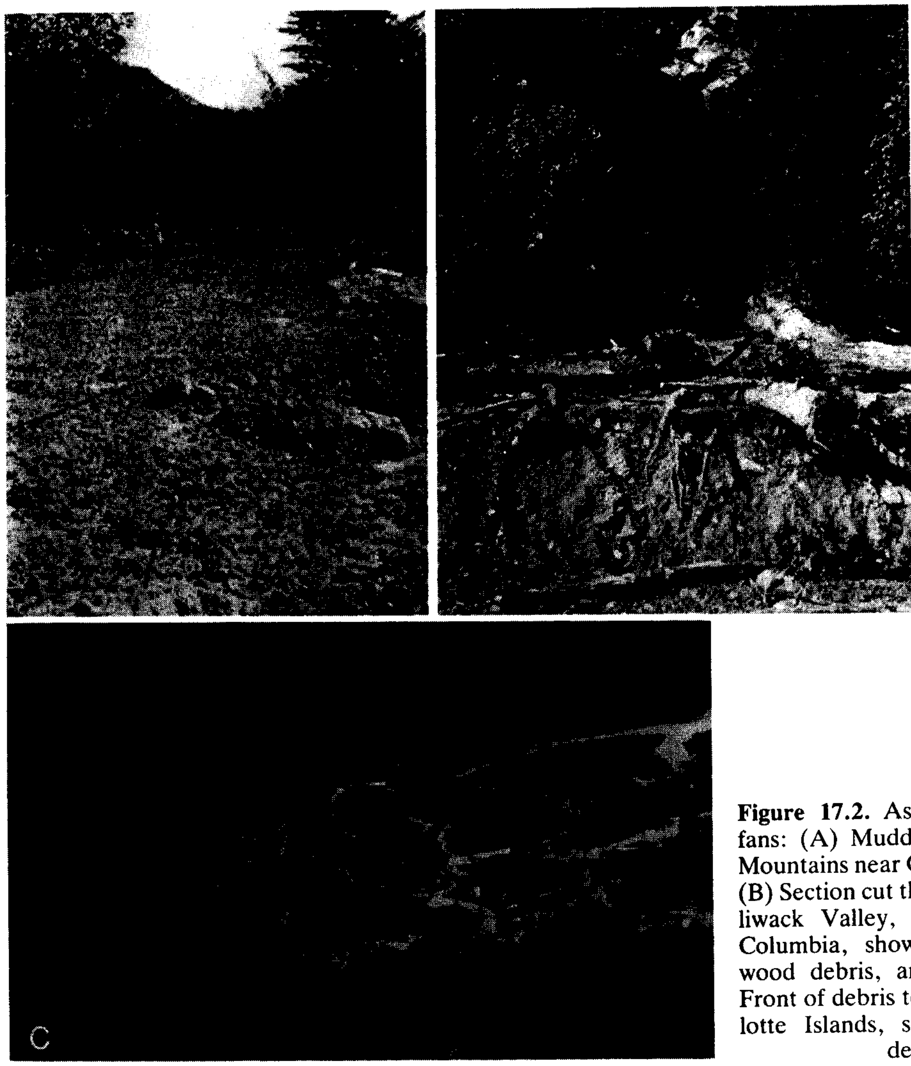


Figure 17.2. Aspects of debris-flows on fans: (A) Muddy, bouldery flow, Rocky Mountains near Golden, British Columbia; (B) Section cut through debris flow in Chilliwack Valley, near Vancouver, British Columbia, showing mud, boulders and wood debris, and lack of bedding; (C) Front of debris torrent in the Queen Charlotte Islands, showing very high wood debris content

> flow', which gradually merges into normal flood flow. Upon reaching flatter gradients or a less confining channel, the surge tends to decelerate and deposition can occur. The liquid after flow may break through the coarse deposits and continue further down the cone.

They indicated that, upon the evidence of the deposits, there appears to be a continuous spectrum of phenomena ranging from debris-flows to fluvial bedload. True debris-flow surges are distinguished from 'mass bedload movements' by the substantial rise of the debris wave above the floodwater level at peak discharge.

Several different hazards occur on fans subject to debris-flow events. The debris-flow front itself tends to contain the very coarsest fractions of the slurry, often involving boulders of several metres in diameter. While travelling at speeds up to $12\ \mathrm{m\ s^{-1}}$ (VanDine, 1985), such bore-like surges of up to 5 m in height can be exceedingly destructive. Since debris surges tend to lose momentum quickly as soon as they escape confinement and can spread out and drain, the danger from direct impact of a surge front diminishes rapidly with distance from the fan apex. However, the relatively rapid arrest of coarse-grained surge fronts high on the fan leads to a second hazard. The arrested surge front often blocks the existing stream channel and the blockage can be far more massive than is achievable during the course of a normal flood event. Apparently well-incised channels can be instantly blocked. Such blockages tend to divert the after-flow of the debris surge and later streamflow to other parts of the fan, often into areas that appeared safe and well beyond the reach of the stream.

Along the coast and on lakeshores, many fans are largely subaqueous deposits. Then the entire terrestrial surface may lie within the fanhead region subject to direct debris-flow impact.

General Hazard Identification

British Columbia has had formal guidelines for the design and review of developments on floodplains since the mid 1970s. These guidelines address such problems as minimum freeboard above flood levels and obstruction of the floodway, but it soon became evident that they do not provide adequate guidance in the case of alluvial fans. In response to this concern, the provincial Ministry of Environment commissioned the writing of a simple manual to help field staff with fan-related problems (Thurber Consultants, 1983a). The manual outlines a systematic procedure for problem diagnosis, emphasizing proper identification and classification of fans.

Clearly the initial and most critical step in dealing with the hazards of alluvial fan development is the proper identification of fans. While this may appear trivial, many investigations have taken off in the wrong direction right at this juncture. Most landuse managers are not trained in geomorphology and when confronted with questions concerning development near streams tend to think in terms of flooding and floodplain mapping. Both are misleading concepts in the case of fans. Fan identification and delineation are deceptively easy looking tasks in sparsely vegetated desert or high alpine terrain—the classical environments for geomorphological studies of alluvial fans—but many significant fans are either densely forested or highly developed, and this often disguises critical features.

The second step involves the classification of fan surfaces into active and inactive areas. Almost all of British Columbia was ice covered only some 12 000 years ago and the period of deglaciation was associated with high sedimentation rates and the deposition of some large fans (Ryder, 1971). Since deglaciation, there have been further significant climatic changes. As a result of this climatic instability, there are now many fan surfaces in British Columbia that may appear fresh, but are no longer aggrading. In practice this means that once a fan has been delineated, its geometry must be determined in considerable detail to see whether there is a relatively uniform, single, conical surface or whether there might be two or more surfaces, as is quite common. In the latter case, only the lowest, actively aggrading surface would likely be subject to hazard from stream avulsions. The entire stream channel or parts of it might also be sufficiently well incised to make avulsions impossible. This would suggest that much or all of the fan is dissected, and therefore inactive and safe.

Channel incision can deceive, however, and it needs to be assessed cautiously. As pointed out above, debris-flows can clog very large channels instantly, but even channels not subject to debris-flows can clog remarkably quickly. The hydrologic regime of the source area might well result in irregular, multiyear periods of channel incision on the fan, followed by rapid channel aggradation and clogging under occasional, relatively rare flood conditions, or in response to an upstream change in landuse or to a forest fire.

Once the presence of an active or potentially active fan surface has been established and delineated, the third step of the investigation should address the nature of the active fan deposition process. All active fans are, by definition, subject to channel avulsions, but the potential for debris-flow magnifies the danger of avulsions and introduces other, more serious hazards.

The British Columbia manual lumps all active fan surfaces together, although the special danger from debris-flows is noted. In the writers' opinion, there is such a great difference with respect to both zoning and types of protective measures between purely alluvial fans and fans potentially affected by debris-flow, that detailed investigations aimed at identifying any potential debris-flow hazard normally are in order.

Debris-flow Indicators

Debris-flow potential may be identified through (a) office investigations and interviews; (b) field study of the upstream channel; or (c) careful examination of the fan deposits. A combination of all three approaches is often needed.

A review of available maps is the obvious starting point since debris-flows typically require steep channel sections of at least 15°, but more commonly 25° (VanDine, 1985) for initiation and, since they tend to start losing momentum and depositing material at about 12°, the apex slopes of fans affected by debris-flows generally exceed 8°. There is a good correlation between the steepness of drainage basins and the steepness of the alluvial fans, so this gradient criterion may be used in a preliminary discrimination in the office of potentially debris-flow prone basins using topographic maps (Jackson and Kostaschuk, 1987). This also constrains the maximum size of the drainage basin, in any particular landscape, that is apt to be debris-flow prone. If the channel and fan slopes fall within the indicated ranges, the obvious next step is to search for records of past events.

Since the phenomenon of debris-flows has only recently been recognized by the engineering community in British Columbia and is still not widely known by the public, past debris-flows are generally reported as either slides or floods. Reports of 'slides' and records of 'washed out' bridges and culverts across steep streams refer, in many instances, to past debris-flows.

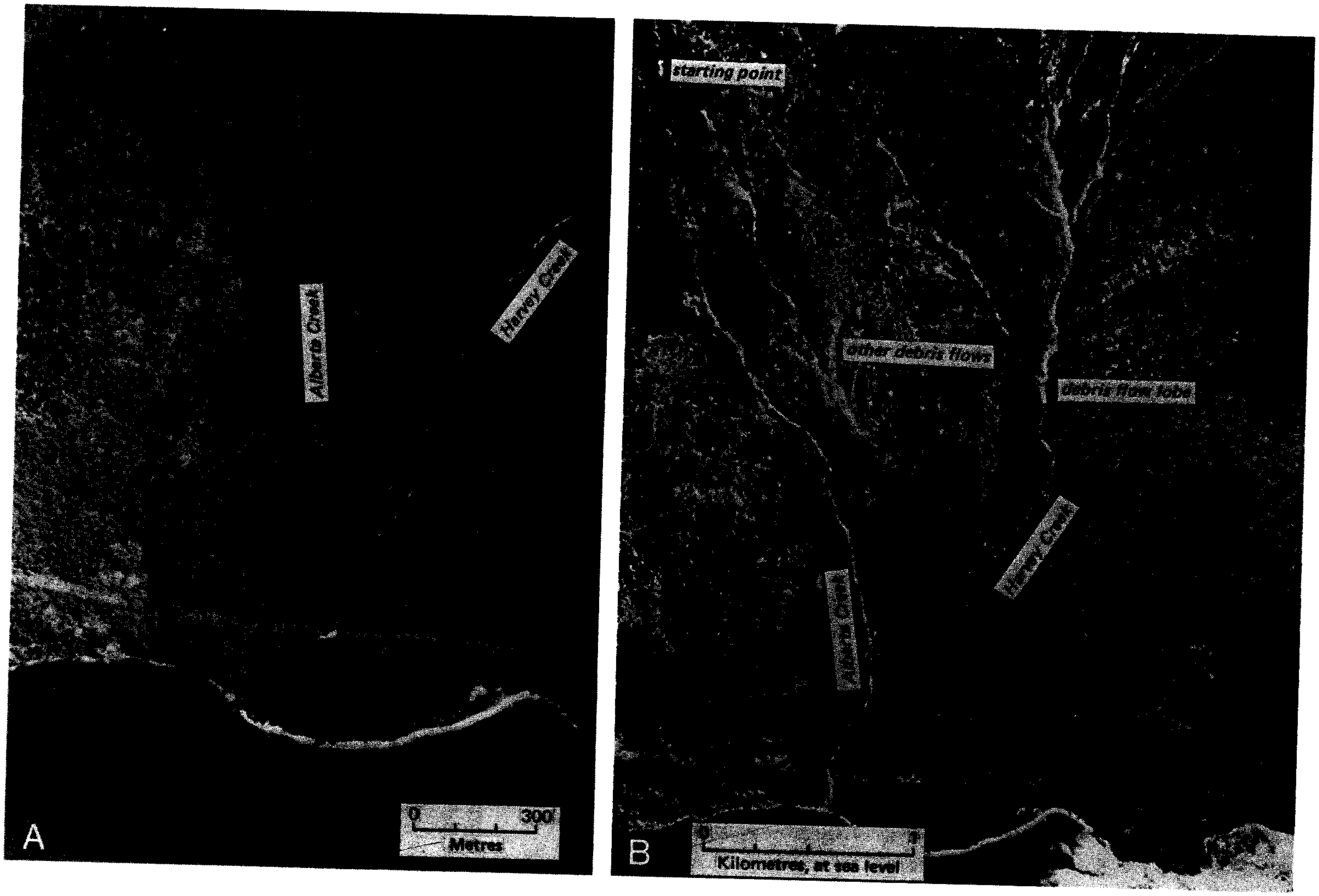
Even though air photos are often available only as far back as the 1940s, and rarely to the 1920s (in Canada), they still provide the most reliable record in most instances because they provide unequivocal visual evidence. Because of the massive scouring, most debris-flow tracks remain easily identifiable on photos for several years. If the tree species that colonize scoured tracks differ from surrounding tree cover, the track may remain identifiable for 50 to 100 years (Smith *et al.*, 1986). In the Coast Mountains and on Vancouver Island, small, steep channels in coniferous forest lined by strips of alder (*Alnus*) or willow (*Salix*) clearly indicate past debris-flow activity or—what is equally dangerous—snow avalanche tracks, since alder and willow are the local colonizing species on exposed mineral soils.

Figure 17.3 shows air photos of the coalescing fans of Harvey Creek and Alberta Creek, on the east side of Howe Sound some 15 km north of Vancouver, British Columbia. The 1939 photo (Figure 17.3B) shows clear evidence of a debris-flow in Alberta Creek that occurred after 1932 (Figure 17.3A). By 1954 (Figure 17.3C), only a detailed ground search for clues would have revealed the past debris-flow activity, and by 1966 substantial development had occurred on the site (Figure 17.3D). Figure 17.4 illustrates the result of the next major debris-flow in Alberta Creek on February 11, 1983. Needless to say, the old air photos were not reviewed prior to the development of this fan.

The desposition zone of the Alberta Creek debris-flows lies mostly below the water of Howe Sound. Where the deposition zone is exposed it may be characterized by stands of dead trees or by the above colonizing species (Figure 17.5). The typical lobate form of debris-flow deposits is not easily identified on air photos, but stands out clearly on large-scale maps of debris cones constructed by ground survey.

Field inspection must address both the channel and the deposition zone. Debris-flows leave many tell-tale signs along the channel that may remain identifiable for centuries and differ significantly from evidence left by normal 'water floods'. Careful inspection of the channel is therefore essential. Some of the signs to look for are:

- boulder levees (irregular lines or mounds of boulders) along relatively flat or less confined channel reaches (Figure 17.6A);
- logs or boulders deposited on either side of the channel or across the channel at elevations that cannot be reached by normal floods (Figure 17.6A);


A
Alberta Creek
Harvey Creek
0
300
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starting point
other debris flows
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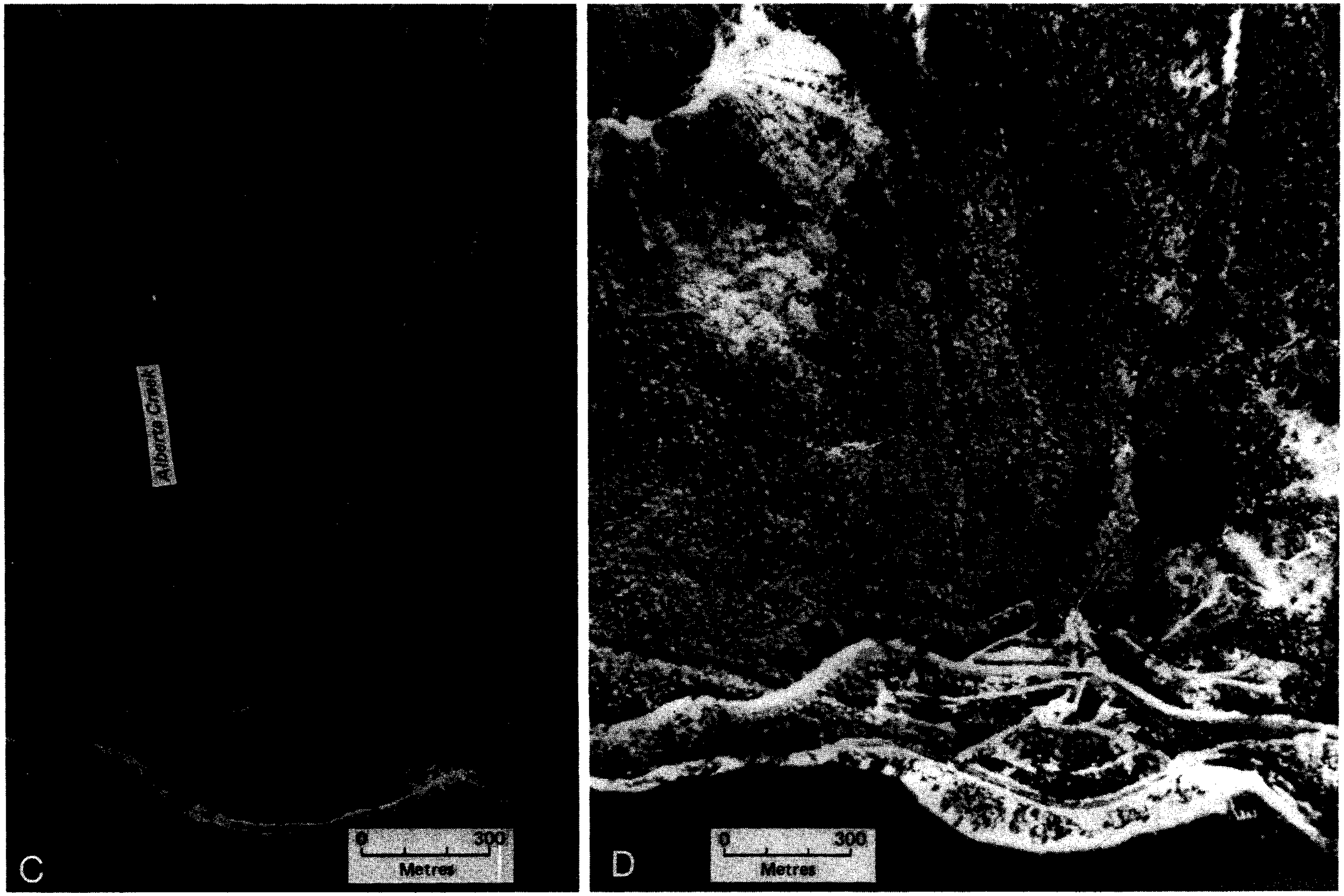

Figure 17.3. The coalescing fans of Alberta and Harvey creeks: (A) Photo A4441: 75, taken in 1932 (National Air Photo Library), before any recent debris torrent. Alberta Creek cannot be detected under the trees; (B) Photo BC143: 80, taken in 1939 (British Columbia, Ministry of Environment, Surveys and Mapping Branch), showing a recent debris torrent running all the way to the sea; (C) Photo BC1682: 56, taken in 1954, showing the new crown closure of the forest vegetation, making it difficult to detect the former debris-flow; (D) Photo BC5175: 106, taken in 1966, showing development of the fan surface for suburban settlement and major transport routes with no protection against potential debris-flows

Figure 17.4. View of the track of the debris-flow of February 11, 1983, where it enters Howe Sound. It is evident that the roads and railway embankment interfered with the flow and affected its route

- debris jams of wood and boulders with some logs splintered, shattered, or broken (Figure 17.6A);
- boulders rolled against trees on either side of the channel (Figure 17.6B);
- pieces of wood buried under boulders (Figure 17.6B);
- scoured bedrock above the highest conceivable flood levels;
- scars on trees along the channel above maximum flood levels;
- differences in vegetation as discussed under 'office investigations'. If this is found, a tree corer can be used to determine ages of trees, hence the minimum age of past debris-flows.

The appearance of the deposition zone varies widely depending on the size of the stream, type and size of sediment and debris being supplied by the basin, and upon the relative importance of normal alluvial sedimentation versus debris-flow deposition. On active alluvial fans the occasional debris-flow deposit, which does not normally extend far down the fan, may be reworked by the stream and will then end up as a true alluvial deposit farther down the fan. In other words, failure to find debris deposits does not indicate security from debris-flow events.

Debris-flow deposits are characterized by boulder levees, irregular and often indistinct ridges or lines of boulders along either side of the runout zone. Debris-flow fronts often come to rest very abruptly, particularly if the debris is coarse, leaving a prominent debris lobe that may be several metres high. During transport, the coarsest materials in a debris-flow tend to ride to the top and to the front of the moving mass and this is likely to be preserved in the deposits (Miles and Kellerhals, 1981). Cuts into debris lobes tend to show boulders on top, supported by a matrix of finer materials with no bedding.

Buried logs, boulders, rolled against trees, bruised trees, and boulders too large to be carried by fluvial processes are other signs of debris-flow activity. If exposures are available in stream banks, road cuts, or other excavations, debris-flow deposits are distinguishable from alluvial deposits by their lack of stratification and imbrication, wide range of sizes, and, occasionally, inclu-

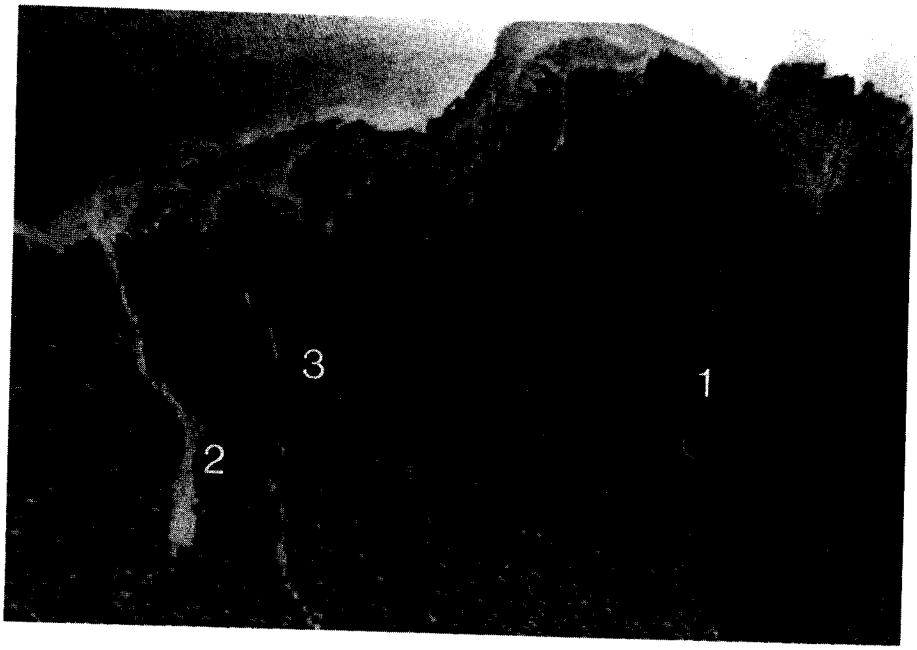

Figure 17.5. Vertical air photo of debris-flow fans in the Queen Charlotte Islands. (1) Lobate debris-flow deposit outlined by distinctive successional vegetation, less than 30 years old; (2) Recent debris-flow incompletely revegetated; (3) Debris tongue that stopped near the top of the fan. The surrounding hillside was logged about 40 years ago and has the same species in the successional forest as occur on the debris-flows. Nonetheless, the deposits remain distinctive because of the different successional stage

sion of organic debris (but it often has decayed and disappeared from ancient deposits). Debris-flow transport also produces less abrasion and, therefore, more angular material than stream transport.

It is naturally pointless to look for boulders if boulder sized material is not available for entrainment upstream, but the converse also is true: if boulders are available in the stream channel, they will almost certainly be moved. The mechanics of debris-flow motion exhibits little dependence upon grain size, so tractive force-based estimates of the maximum grain size that can be moved by a large flood are irrelevant.

Hazard Avoidance through Classification and Zoning

By definition, all active fan surfaces are subject to one or both of avulsion and debris-flow, but the frequency and severity of events vary by many orders of magnitude. Unlike the case of floodplains, where water levels and associated return periods provide an objective and widely accepted classification of the degree of exposure, there are no broadly accepted standards for classifying hazards on fans.

AVULSIONS

Although avulsions almost always occur during major floods, the probability laws governing avulsions differ greatly from those of floods. Dawdy (1979: *cf.* discussion in French, 1987) attempted to analyse the probabilistic aspect of flooding on alluvial fans but, in order to make the problem tractable, he had to adopt several restrictive and questionable assumptions. In particular, the assumption that 'the degree of flood hazard is approximately equal for all points that are radially equidistant from the fan apex' may have some

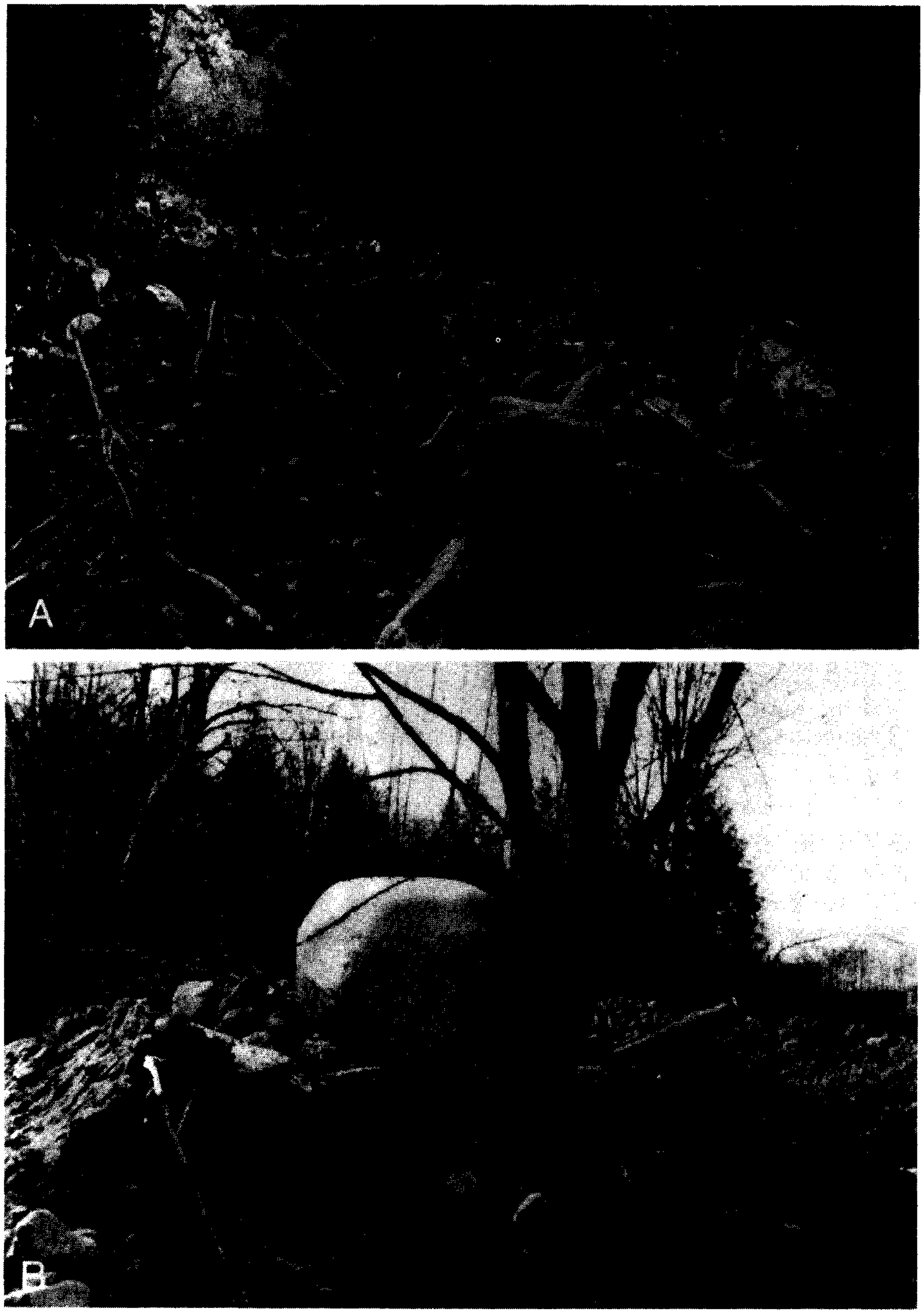

Figure 17.6. (A) Upstream view over the left bank boulder levee of a recent debris-flow: location near the fan apex; (B) A boulder at rest against a tree in the runout zone of a debris-flow, in the mid-fan area. Note also buried wood debris

merit on large fans with ill-defined, unstable stream channels and a dominance of sheet flooding in semiarid regions. However, on most British Columbia fans it is not realistic because of transient topographic constraints.

Contrary to most flood-generating processes, the process of channel avulsion can have a relatively long memory. When a stream finds itself a new path across a fan, it tends to follow a topographically low route and will therefore be initially quite stable in its new course. However, with time, aggradation will proceed along that route. Eventually it will become a topographic high and a new avulsion will become progressively more likely. These alternating periods of stability and instability may last from days to centuries. The consequence of the former situation is obvious in most hazard assessments, but the latter is not. On a fan with a history of infrequent avulsions, the stability of the existing channel location must be assessed carefully. At the same time one should look for steeper and more direct alternate routes across the fan. This is of interest both for design of remedial measures and for detailed hazard assessment on the fan. Any sites along alternate, more direct channel routes are particularly vulnerable. Figure 17.7 illustrates a fan on which the inevitability of eventual avulsion is avoided only through annual removal of gravel from the active channel along the entire length of the fan: the measure is necessary to protect the highway bridge at the toe.

The Thurber Consultants (1983a) report, 'Floodplain management on alluvial fans', recommends the classification of fan surfaces into 'very active', 'moderately active', and 'slightly active' subareas based on activity indicators such as the following:

- high sediment supply from the upstream catchment;
- degree to which the fan has displaced the main river to which the fan stream drains (an indicator of sediment supply rate);
- debris-flow potential;

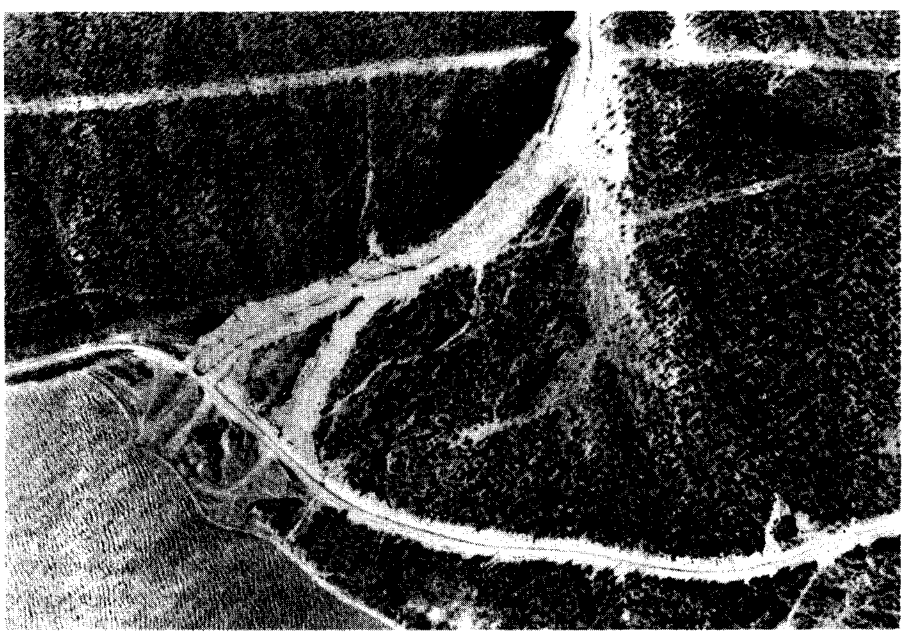

Figure 17.7. Alluvial fan of Williscroft Creek at Kluane Lake, Yukon Territory. The channel on the right hand side of the fan must be cleared by bulldozer after major storms to maintain the stream in the course to the bridge which carries the Alaska Highway over it

- steep land and stream gradients;
- potential for flash floods;
- large number of abandoned or secondary channels;
- a high ratio of active channel area to total fan area;
- a high watertable on the fan surface as an indicator of a relatively high and therefore unstable channel position.

This classification obviously could be refined considerably further after detailed mapping of potential avulsion routes. A similar classification was developed in the detailed regional study discussed in the next section (see Table 17.2).

DEBRIS-FLOW

Debris-flow occurrence has an even more uncertain and complex probabilistic structure than the occurrence of fluvial avulsions because there are two types of debris-flow channels. Some, mostly bedrock controlled, channels are occasionally cleaned of accumulated debris by a debris-flow. In the period immediately following such an event the probability of further debris-flows may be very low due to lack of readily available debris in the channel.

Debris-flow channels incised into deep, unconsolidated materials can, however, act differently. They tend to be destabilized by the occurrence of a debris-flow and can then remain active for decades because there is an unlimited supply of debris right in the channel bed and banks. A long period of low flows eventually allows them to regain stability, usually by vegetation succession. As a consequence, debris-flows in this type of channel tend to occur in groups that may be separated by decades or centuries of deceptive tranquility.

Bovis and Dagg (1987) have made a detailed study of debris supply mechanisms to the Howe Sound creeks near Vancouver which illustrates the contrast in behaviour between the two types described, and also shows that the influence of geology on the calibre of debris introduced to the channel may be important. Very coarse, blocky debris cannot be moved by normal fluvial processes, and so it builds up over long periods to form a dangerous charge for debris-flows.

Besides having long-term memory, the stochastic process of debris-flow occurrence is strongly affected by landuse changes or forest fires in the upstream basin. O'Loughlin (1972) found, on the basis of data from the Coast Mountains in southwestern British Columbia including the Howe Sound sector, that clearcut logging and, particularly, logging road construction increased the occurrence of landslides. More recently, Rood (1984) found a 34 times increase in the frequency of landslides due to clearcut logging and the associated road building in an area of steep and generally unstable terrain in the Queen Charlotte Islands of British Columbia. Many of the landslides entered stream channels and triggered debris-flows.

Some channels are fed debris by an individual, very large failure in bedrock or unconsolidated material which may remain active for centuries or even millenia, then finally stabilize. Hence, very long-term episodic behaviour may be superimposed upon the patterns described above.

For fans exposed primarily to debris-flow hazards the approach adopted by Thurber Consultants (1983b; see also Hungr *et al.*, 1987) is of interest. This second Thurber study was initiated after a debris-flow swept away a wooden bridge across M Creek, north of Vancouver, on a rainy autumn night. Nine lives were lost when several automobiles drove into the swollen stream and were swept into Howe Sound. M Creek is located along the same stretch of road as Alberta Creek, illustrated in Figures 17.3 and 17.4. The disaster focussed concern on the fact that there are many similar fans along Howe Sound, all crossed by a major highway and a railway line. Some are also developed extensively for housing. The Thurber Consultants study (1983b) was commissioned by the British Columbia provincial government in response to this concern. The objectives were to review and classify the flooding and debris-flow hazard along a 29 km stretch of the highway involving 26 stream crossings.

A two-step approach was adopted to debris-flow hazard classification. The first step involved a detailed examination of the channel and catchment upstream of each fan, combined with a review of all historical records and the identification and dating of debris-flow deposits on the fan. The outcome of this assessment was the assignment of each stream to one of the four debris-flow occurrence classes shown in Table 17.1 and an estimate of the 'design' debris-flow volume for each stream. This volume is defined as 'a reasonable upper limit of the quantity of material involved in future large debris torrents'. It is intended primarily for planning and bridge design purposes. A single design event may include several surges. The basis for this design volume is primarily an estimate of the total quantity of debris that is currently available for entrainment in the stream channel or, if a channel has recently been scoured by a debris-flow, it is the quantity of material that might be available in the foreseeable future. Only the normal debris-generating processes are considered: a large slope failure continuing down the channel as a debris-flow could result in greater volumes (Hungr *et al.*, 1987). The debris volume estimates do not involve frequency considerations, but they are being applied to bridge and dyke designs for which the 200-year flood is the normal design criterion in British Columbia.

The second step in Thurber Consultants' hazard classification involved hazard mapping of the fan surface according to a classification like that of Table 17.2. The three T-type classifications codify debris-flow hazards while the three F-type classifications refer to hazards related to normal processes on alluvial fans; i.e. avulsions and flooding. All but two of the 26 study fans were hazard zoned according to debris-flow clas-

Table 17.1. Probability of occurrence of debris flows*

Category	Description
4	*Very high probability of occurrence:* indicates that debris flows of less than the design magnitude can occur frequently with high runoff conditions, and the design event should be expected within the next 10 years. It is applied to streams that have a recent history (<30 years) of more than one event involving greater than 500 m^3 or have physical characteristics that are comparable to such streams.
3	*High probability of occurrence:* indicates that debris flows of less than the design magnitude will occur less frequently than under category 4 but the design event should still be expected within the short term (<10 years). It is applied to streams that have a recent history of a single debris flow event and to streams that have no history of events but physical characteristics comparable to those of category 3 streams.
2	*Moderately high probability of occurrence:* indicates that the design debris flow should be assumed to occur during the life of structures such as residences or permanent bridges. It is applied to those streams that have physical characteristics that fall well within the regionally observed threshold where debris flows are possible, although not in the range of category 4. Such streams generally have no recent history of debris flows, but may have experienced events of uncertain origin.
1	*Low probability of occurrence:* indicates a low potential for the design debris flow. It is applied to those streams whose physical characteristics place them at or close to the threshold where debris flows are possible. Although a significant debris flow is possible during the life of structures such as residences or bridges, it would require an unusually high (and thus infrequent) runoff condition.
0	*No risk:* indicates that there is virtually no potential for large debris flows, although small and local events may occur, and flows of varying magnitudes might develop in upper reaches and tributaries. It is applied to channel reaches whose physical characteristics fall well below the threshold where debris flows are possible.

*Modified from Thurber Consultants (1983b).

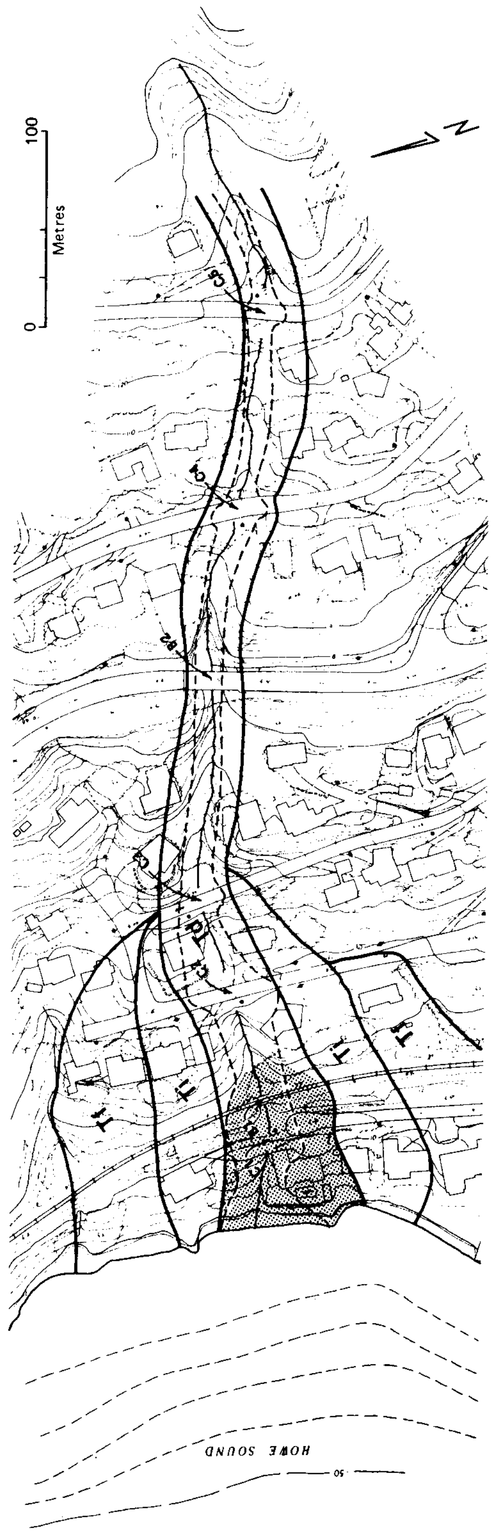

Figure 17.8. Hazard zones on the fan of Alberta Creek, as determined by Thurber Consultants (1983b)

Table 17.2. Fan hazard zone classification*

Category	Description
Td	*Direct impact zone of debris flows:* zone through which the debris surge may travel. The risk of impact damage is therefore high. Material transported through this zone could include boulders up to several metres in diameter and logs over 30 metres long.
Ti	*Indirect impact zone of debris flows:* zone through which later debris surges may be diverted and/or through which after-flow may travel. The risk of impact damage is lower. Material could include large rock and log debris, but is more likely to contain boulders of less than 1 m to fine-grained material and organic mulch.
Tf	*Flood zone due to debris flows:* zone that is exposed to flooding as a result of blockage of the main channel by debris-flow deposits. The risk of impact damage is low. Fine-grained material and mulch could be contained in the flood water.
	Area of potential deposition of debris: areas within which debris-flow materials could be deposited.
	Outline of area directly affected by known previous events: refers to historical events rather than to ones known only from morphology or stratigraphy, and of uncertain date.
Fh	*High flood hazard zone:* zone that has a high probability for flooding. In this zone, avulsions are possible.
Fm	*Moderate flood hazard zone:* zone that has a moderate to high probability of flooding. Avulsions could occur but are unlikely.
Fm	*Low flood hazard zone:* zone that has a moderate to low probability of flooding, but avulsions are unlikely.

*Modified from Thurber Consultants (1983b).

ses. The two largest fans were judged to be free from debris-flow hazard but exposed to avulsions and flooding, and were accordingly zoned into F-classes. By implication, the maximum size drainage basin which appears to be susceptible to debris-flow in the Howe Sound study area has an area of about 10 km^2. There probably are many fans that should be zoned into both T and F classes, but this did not appear to be necessary in this particular area. Figure 17.8 illustrates the hazard zoning for Alberta Creek, the stream illustrated in Figures 17.3 and 17.4.

Since completion of the zoning study, there has been only one debris-flow event—of 5000 m^3 in Sclufield Creek—on the 26 streams studied. The design volume listed in Thurber Consultants (1983b) for that fan is 6000 m^3. A map of the deposition is shown in Hungr *et al.* (1987). Approximately 10% of the actual deposition zone was found to lie outside the designated Ti and Td zones.

Protective Works

AVULSION HAZARD

In situations where it is not feasible to avoid the hazards associated with developments on fans, a wide array of protective devices have been used. Channel avulsions can be prevented by dyking the channel, by artificially incising it, or by increasing the transport capacity across the fan with measures such as channel straightening, channel lining, or channel enlargement. In British Columbia, where both land values and earth moving costs are relatively low, riprap dykes, channel enlargement, channel incision, and channel straightening, or a combination of these measures are the normal solutions. No smoothly lined, chute-like channels of the type so frequently seen in the Alps and in Japan have yet been built to deal with fluvial avulsion hazards.

Thurber Consultants (1983a) described five fans that were selected to exemplify the range of problems typically met in British Columbia. Besides hazard avoidance zoning, detailed mapping to identify potential avulsion routes, and the active measures mentioned above, the study also recommends large lot sizes combined with construction on slightly elevated pads to ensure that the fans do not become densely cluttered with buildings and that buildings will not be directly in the path of future avulsions.

In an increasing number of situations, dyking on partially developed fans has lead to rapid aggradation within the dykes. In such situations, debris interception basins are considered. However, there exist no straightforward criteria for determining the desirable basin capacity. Bedload sediment transport equations are generally not valid in the steep upstream channels. The one purpose-designed equation extant (Smart, 1984) is based upon laboratory experiments with a plane bed. Irregular, step-pool mountain channels pass bed material at much lower rates. Indeed, even coarse debris transport rates may be supply limited. In this circumstance, regional storm magnitude-sediment yield correlations may provide a best basis for design, but such data are almost nonexistent.

DEBRIS-FLOW HAZARD

In situations where debris-flows are the main hazard, protective measures implemented in British Columbia range from simple tripwire warning devices to debris chutes, large diversion dykes, and debris storage basins. The long staircases of check dams and extensive slope drainage works that are so prevalent in Japan and in the Alps have no equivalent in British Columbia for reasons that are primarily economic but may be partially cultural. The centuries-old Asian and European traditions of landscape gardening appear to have been left behind by the emigrants to North America. Of course, sound forest land management is recognized as important to minimize erosional mobilization of debris in the first place. Hungr *et al.* (1987) provide a comprehensive, detailed description of all types of debris-flow defences implemented in British Columbia so far.

Debris chutes are effective in situations where debris deposition on the lower parts of the fan is acceptable. Figure 17.9A shows the debris chute of Alberta Creek (see Figures 17.3 and 17.4). Chutes are often a good solution in the case of bridge crossings on undeveloped fans since they confine the debris-flow to a fixed channel and help prevent bridge openings from becoming clogged (Figure 17.9B).

Large diversion dykes, as illustrated in Figure

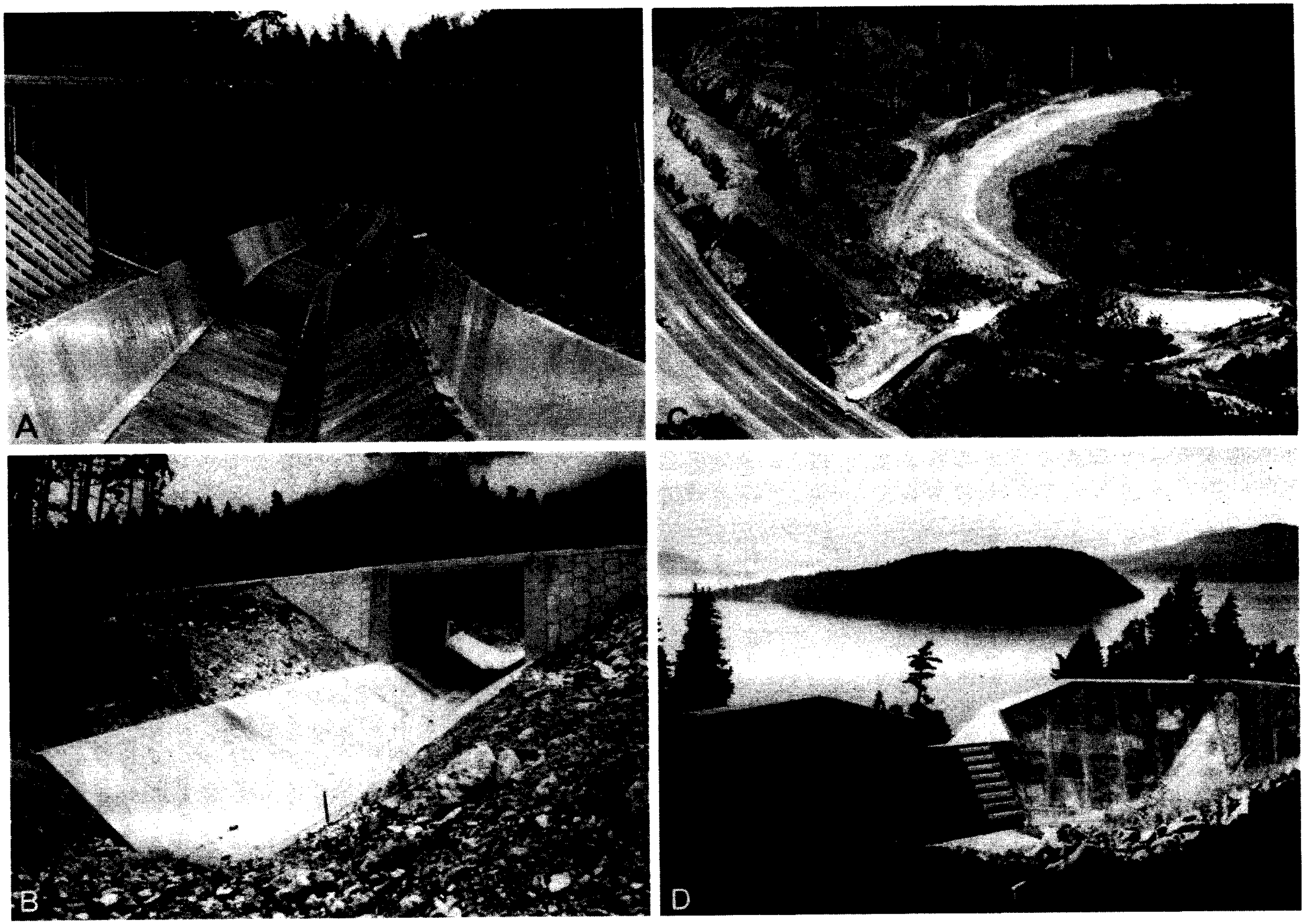

Figure 17.9. (A) Alberta Creek debris chute constructed after the February, 1983, debris-flow (Figure 17.4); (B) Bridge opening with debris chute; (C) Debris flow diversion dyke. A debris storage area of 12 500 m^3 capacity is created by a 5 m high dyke. The dark material within the dyke is the deposit of a debris-flow. Photograph courtesy of Thurber Consultants, Ltd. and Dr. Oldrich Hungr; (D) Debris interception barrier on Charles Creek. See Hungr *et al.* (1987) for a detailed description of the design. Photograph courtesy of Mr. Michael Younie

17.9C, are often the preferred solution in British Columbia if space permits. They do, however, require careful maintenance. Any significant debris deposits behind the dykes must be removed if eventual overtopping is to be avoided. Nasmith and Mercer (1979) describe the design of a system of diversion dykes to protect the town of Port Alice. This industrial 'instant town' is located on a large debris-flow fan along one of Vancouver Island's west coast fjords. The debris-flow problem became apparent only some eight years after the town was built. Another case, on a much smaller scale, is described by Martin *et al.* (1984): in this instance, dykes and an interception basin were used to protect a prison built partly on a debris-flow fan.

Debris interception basins at or above the fan apex are generally the most expensive solution and have the most stringent maintenance requirements, but there is little interference with existing fan developments. Basin capacity may in this case be estimated on the basis of debris-flow volume criteria discussed above. Three of the 26 streams studied by Thurber Consultants (1983b) were eventually judged to pose sufficient hazards to existing residential developments and to the highway and railway crossings to warrant the construction of interception basins. Figure 17.9D illustrates the basin on Charles Creek. It is formed by a rockfill dam designed as a water retaining structure. The basin can hold the design debris volume and the overflow chute can accommodate a second design flow volume. The detailed design considerations are described by Hungr *et al.* (1987).

Conclusions

Fans can be deceptively hazardous sites. In British Columbia, much development has proceeded without a clear appreciation of these hazards and this has led to loss of life and much property damage, but it has also stimulated interest and encouraged systematic approaches to alleviating existing problems and to avoiding new ones.

In classifying hazards on fans, it is critically important to recognize any debris-flow potential since the problems associated with debris-flows differ greatly from the problems posed by normal alluvial fan processes. Fully objective fan hazard classifications that would correspond to floodplain delineation at a specific return period are not feasible because of the complex and ill-defined probabilistic structure of both 'avulsion occurrence' and 'debris-flow occurrence'. Even in the European Alps, records are generally too short and past climate and landuse too uncertain to define these processes. However, somewhat subjective classification schemes that incorporate observations and experience do offer practical alternatives to rigorous statistical analysis.

Protective measures implemented in British Columbia differ somewhat from those commonly employed in the European Alps and in Japan because of the relatively low land values, lower earth moving costs, and lower population densities typical of North America. Diversion dykes, debris chutes, and interception basins placed within the occupation zone on the alluvial fan are the major means selected. Upstream channel improvements are not attempted, and drainage basin land management is restricted to careful forest landuse.

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