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UNIVERSITY OF ALBERTA

Risk Analysis for Rock Fall on Highways

BY

Christopher M. Bunce ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

IN

Geotechnical Engineering

Department of Civil Engineering

Edmonton, Alberta

Fall 1994

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UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and research for acceptance, a thesis entitled Risk analysis for rock fall on highways submitted by Christopher M. Bunce in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

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June 10, 1994

Abstract

Transportation corridors through mountainous terrain are often susceptible to rock fall hazards. Rock falls can cause delays, damage, injury, and death to users of these routes. In 1982 a rock fell on a vehicle killing a woman and disabling her father on B.C. Highway 99. The father successfully sued the provincial Ministry of Transportation and Highways for damages after pursuing his claim to the Supreme Court of Canada. The Supreme Court of Canada and subsequently the British Columbia Supreme Court decided that the Ministry was at fault for not preventing a readily foreseeable event that might harm users of the highway.

This research demonstrates a method of rock fall impact mark mapping supplemented by documented rock fall records, to establish a rock fall frequency. A methodology for assessing the risk of loss of life due to rock fall is also developed. This methodology is applied to the above case and the results compared with accepted societal risks. The Rockfall Hazard Analysis System, developed by the U.S. Federal Highways Administration, is also correlated with the risk analysis results at this site. The risk analysis indicates that the risk posed by rock fall is comparable to other risks in society and may be within levels proposed for other types of slope instabilities.

On a route like B.C.'s Highway 99, there are a large number and wide distribution of potential rock falls. Due to the expense of remediating each one, it is not considered practical to control all the potential rock falls. As a result, society must accept some level of risk. In finding the Ministry at fault in the Just case, the British Columbia Supreme Court may have set the acceptable level of risk for injury or death due to rock fall below a level that is economically achievable or considered reasonable compared with other accepted risks.

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Risk analysis for rock fall on highways

Table of Contents

List of tables

List of figures

Glossary

Due to the three types of rock fall vehicle interactions and two types of risk calculations considered in this research, several variables are introduced. The following is the definition of each variable. In an effort to ease understanding, Morgan's (1992) nomenclature has been followed where possible. In addition, abbreviations used are defined.

AADT	annual average daily traffic volume
AASHTO	American Association for State Highway and Transportation Officials
Alta Cr.	Alberta Creek
ASD	actual sight distance of a portion of highway (Pierson et al. 1990)
DSD	decision sight distance (AASHTO 1990)
CHSL	Capilano Highways Services Limited
CRSP	Colorado Rockfall Simulation Program
EAADT	Estimated annual average daily traffic volume
F_v	average fraction of the highway occupied by vehicles
H. Bay	Horseshoe Bay
L_c	length of a highway rock cut
L_{dsd}	length of the decision sight distance for a specific vehicle speed (AASHTO 1990)
L_{rf}	length of the road effected by a rock fall
L_v	average length of vehicles using the highway
MOH	Ministry of Highways, British Columbia
MOTH	Ministry of Transportation and Highways, British Columbia
msl	mean sea level
N_a	number of vehicle/rock accidents resulting from a specific number of rocks reaching the road in a given time period
N_r	number of rocks that reach the road annually
N_v	number of vehicles at risk which is equal to the number of vehicles that pass through the cut per day or are stationary within the cut for a given period
P(A)	probability of a rock hitting a vehicle or a vehicle hitting a rock
P(D)	probability of death for the population exposed to the hazard for a particular time period (Whitman 1984)
PDI	(Morgan 1992) is the probability of death of a specific individual
PDSD	percentage decision sight distance
P(H)	probability of a hazardous event occurring (Morgan 1992)

P(L:T)	probability of loss of life of an individual given a rock hits the individual's vehicle (Morgan 1992)
P(S)	probability that a rock hits a vehicle and is therefore the combination of P(H) and P(S:H) from Morgan (1992)
P(S:H)	probability of spatial impact given the event or the probability that a vehicle occupies the portion of the road effected by a rock fall (Morgan 1992)
P(T:S)	probability of temporal impact given spatial impact (Morgan 1992) or the probability that a vehicle occupies the rock fall path when the rock impacts the road
PAV	probability of a rock fall/vehicle accident of an individual vehicle
RHRS	Rockfall Hazard Rating System (Pierson et al. 1990)
SADT	summer average daily traffic volume
S_V	vehicle spacing in a line of stationary vehicles
t	time vehicles are at risk: either the travel time of a vehicle moving through a cut or the time a vehicle is stationary within a cut
Vv	average vehicle speed which is assumed to be equal to the posted speed limit
WSDOT	Washington State Department of Transportation

Risk analysis for rock fall on highways

1.0 Introduction

Transportation corridors through mountainous terrain are often susceptible to rock fall hazards. Rock falls can cause delays, damage, injury, and death to users of these routes. In 1982, a rock fell on a vehicle killing a woman and disabling her father while they were delayed in traffic on British Columbia Highway 99. The father, Mr. Just, successfully sued the provincial Ministry of Transportation and Highways for damages after pursuing his claim to the Supreme Court of Canada. The Supreme Court of Canada (Cory J. and Sopinka J. 1989) and the Supreme Court of B.C. (Donald J. 1991) determined that the rock fall that injured the claimant was a foreseeable event, and therefore should have been prevented from harming the highway users.

Clearly, society has limited resources available to minimize natural hazards. Therefore, society must accept some level of risk. If a specific risk is lower than that accepted by society, the expenditure of resources to reduce that risk is inappropriate. Alternately, if a risk is higher than the accepted level, society requires a method of assessing how best to allocate its efforts to achieve the greatest benefit. Risk analysis procedures such as those suggested by CAN/CSA (1991) provide a framework for investigating hazards, and their impact on specific groups or society as a whole.

Reaction to loss of life from a rock fall is often magnified by the tendency of the public to react more rigorously if the event is infrequent. This reaction may lead to public demand for the removal or reduction of the hazard. Before resources are expended, this emotional reaction should be tempered with a logical assessment of the problem. Risk analysis provides a methodology for rational investigation of the comparative benefit of different measures to reduce risk.

This thesis includes a methodology for assessing the risk of being negatively affected by a rock fall while on a highway. In addition, the risks associated with the circumstances of the previously described Just v. B.C. Case, are quantified. The results can be used to determine if rock falls present an unacceptable risk to highway users, and if so, which areas pose the greatest risk.

The research has five stages:

1. review of the literature on rock fall; rock fall accidents, modeling, and mitigation; risk analysis and legal cases involving rock fall (section 2.0)
2. overview of the CAN/CSA (1991) risk analysis guidelines (section 3.0)
3. development of risk analysis methodology within this framework (section 4.0)

4. the application of the methodology to the Just Case (section 5.0) including: reviewing highway accident records, traffic statistics and rock falls information from the B.C. Ministry of Transportation and Highways (MOTH) (section 5.3.4 and 5.3.7); field data collection from the location of the Just Case (section 5.3.3); and the application of the U.S. Federal Highway Administration Rockfall Hazard Rating System (Pierson et al. 1990) (section 5.3.3.2).
5. calculation of the risk in the Just Case (section 5.4)
6. comparison of the risks at the time of the Just Case and other societal and individual risks (section 6.0)

The research draws on information from several different sources, including slope stability engineering, transportation engineering, highway maintenance, risk analysis, legal precedent and meteorologic data. As a result, the terminology, abbreviations and methodology used in this research are adapted from all of these fields. The glossary on pages xi and xii contains the definitions of the abbreviations and terms used in the text.

1.1 Purpose of research

The risk analysis of rock fall on highways is of interest to several disciplines. The Canadian Supreme Court has ruled that agencies responsible for maintaining highways may be liable for compensating victims of rock falls (Cory J. and Sopinka J. 1989). Therefore, highway authorities are interested in assessing and mitigating the risk of rock falls. Judicial authorities need assessments of rock fall risks to compare the dangers posed by rock fall to other risks accepted in our society, both involuntarily and voluntarily. From an operational and safety point of view, the possibility of rock fall is of concern to the engineer designing a transportation corridor. Often public concern is voiced regarding the risks of specific highways. Information quantifying the risk of rock fall on a highway may be applicable to some of the public's concerns. Police and emergency response teams are interested in the risk of rock fall, because it affects the safe use of highways. Maintenance requirements and costs are increased by the hazard of rock falls and the damage resulting from rock falls. The insurance industry also has an interest in losses related to rock fall, because they can be required to compensate insured victims.

Risk assessment of rock fall hazards has two applications. Initially, it allows the ranking of the rock fall risks among other risks present in society. Second, when rock fall risks exceed the risk level accepted by society, it may encourage the appropriate allocation of manpower and resources to address those areas that pose the highest risk.

The broad range of interest in the risk associated with rock falls on highways makes this a valuable research topic.

2.0 Literature review

2.1 Background

This study focuses on a section of B.C. Highway 99 between Vancouver and Squamish where a rock fall killed the passenger and injured the driver of an automobile. The injured party, Just, successfully sued the B.C. MOTH for damages resulting from this rock fall below the "Argillite Cut" (Donald J. 1991, p. 214, MOTH 1982, 1988, and 1992).

Several methodologies are available for quantifying risk. The Canadian Standards Association published a document (CAN/CSA 1991) on risk assessment containing a review of possible methodologies. This document forms the framework for the risk analysis methodology developed in section 4.0.

2.2 Risk analysis of geotechnical hazards

Risk analysis in geotechnical engineering takes many forms. Hartlen and Viberg (1988) presented an overview of terminology, and hazard and risk assessment techniques. Hazard and risk mapping approaches have been presented by Brand (1988), Einstein (1988), Romana (1988, 1991) and in the landslide hazard assessment session of the 6th International Conference on Landslides (Bell 1991, Vol. 2. pp. 855 - 1085). Chowdhury and Tang (1987), Chowdhury (1988), and Bosscher (1988) have assessed risk of failure based on the variability and uncertainty in input parameters to various stability analysis. Alternatively, Hunt (1984), Fell (1994), Morgan et ai. (1992), Morgan (1991), and Varnes (1984) defined risk as a measure of the probability of an event and the resulting death, injury or damage. It is this latter form of risk assessment that is the focus of this research

In the past, some authors (Hunt 1984, Walker 1987) have prescribed the application of qualitative risk analysis representing risk with terms like high, medium and low. Walker et al. (1987) reviewed the application of four qualitative and semi-quantitative risk assessment techniques for instabilities in soil. Varnes (1984), Brand (1988) and Einstein (1988) present examples of risk mapping. Hunt (1984 and 1992) proposed a five level risk degree rating that included rock fall as an example of a low risk. Recently there has been an increased focus on quantitative risk analysis. Fell (1994), Morgan (1991), Morgan et al. (1992), Golder Associates (1993) have all presented examples of quantitative risk analysis. Fell (1994, p. 269) also included a semi-quantitative system for projects in which it is not "economically feasible to accurately quantify the risk".

Whitman's (1984) 17th Terzaghi lecture on evaluating risk in geotechnical engineering discussed statistical uncertainty in design parameters and the resulting probabilities of failure that can be derived. He also identified the need to put geotechnical risk evaluations into a context with other natural and man-made risks and address those hazards that present the greatest risk.

Fell (1994) has compiled an extensive review of landslide risk assessment and acceptable risk. Although Fell does not consider rock falls specifically, his risk criteria for landslides are applicable to rock falls. This extension is supported by Cruden and Varnes' (1994) classification of rock falls as landslides.

Fell (1994), UNDRO (1992) and the CAN/CSA (1991) have proposed definitions for risk assessment terminology that are adopted by this study. These definitions are adapted here with respect to rock falls.

Classification - is a description of the nature of the rock fall(s) or potential rock fall(s) following Cruden and Varnes' (1994) classification.

Hazard $\{H\}$ - is a threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area (UNDRO 1992, p. 4). In a broad sense, $H = M * P$ (Fell 1994, p. 262)

Magnitude $\{M\}$ - is the volume of the rock fall(s) (Fell 1994, p. 262)

Probability $\{P(H)\}$ - is the probability that a rock fall occurs within a given period of time (generally a year) (Fell 1994, p. 262)

Risk - is the expected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability (UNDRO 1992, p. 5).

Specific risk $\{R_s\}$ - equals the probability times the vulnerability for a given element = $P * V$ (Fell 1994, p. 262).

Elements at risk $\{E\}$ - means the population, properties, economic activities, including public services etc. in the area potentially affected by the rock fall(s) (Fell 1994, p. 262).

Total risk $\{R_t\}$ - is the expected number of lives lost or injured, damage to property, or loss of economic activity or environment. It is the product of specific risk $\{R_s\}$ and elements at risk $\{E\}$ over all rock falls and potential rock falls in the study area. Therefore $R_t = \mathrm{Sum}\{E * R_s\} = \mathrm{sum}\{E * P * V\}$ (Fell 1994, p. 262)

Vulnerability {V}	- is the degree of loss to a given element or set of elements within the area affected by the rock fall(s). It is expressed on a scale of 0 (no damage) to 1 (total loss). (Varnes 1984, Fell 1994)
Risk analysis	- is a three step process involving scope definition, hazard identification and risk estimation (CAN/CSA 1991).
Risk estimation	- includes frequency analysis, consequence analysis and their integration (CAN/CSA 1991).
Risk evaluation	- the stage at which values and judgment enter the decision process (CAN/CSA 1991).

Consistent with Fell (1994) the author has adopted the technique presented by Morgan et al. (1992) for quantifying vulnerability .

$$V = P(S:H) * P(T:S) * P(L:T)$$

where P(S:H) is the probability of spatial impact, i.e. that a vehicle is affected by a rock fall given that a rock fall occurs. P(T:S) is the probability of temporal impact, i.e. that the vehicle occupies the location of the rock fall impact given that it occurs. P(L:T) is the probability of loss of life of an individual occupant or the proportion of the impacted vehicle which is damaged.

Although Morgan et al. (1992) identified the probability of a large debris flow, P(H) as being the most difficult parameter to establish, in the case of rock falls on a roadway, the probability of death, P(L:T) is also uncertain. Morgan (1991) assumed a P(L:T) of unity in his discussion of slope hazards, because the size of the slide under consideration would almost certainly result in loss of life assuming spatial and temporal impact.

Fell (1994, p. 267) also states that "it is essential that one clearly defines the element at risk, and it can be useful to consider a smaller element (e.g. a room in a house) as well as the overall house to assess the total risk, because one can more readily assign vulnerability to the smaller elements." This is true for rock fall on a highway, but it also has disadvantages. For example, it is reasonable to assume a P(L:T) of unity when considering a vehicle's driver seat as the element at risk. The disadvantage to smaller elements is the requirement for multiple risk analysis to assess the risks of passengers being killed or of the vehicle being damaged.

With respect to the cost of landslides, Fell indicated that large areas have a potential for landsliding, and that "The annual direct cost of landsliding in such areas is in fact relatively small, and is almost certainly less than the annual cost of sterilizing the land" (1994, p. 261). Similarly, Evans and Hungr (1993, p. 622) stated that in Canada "the indirect cost of sterilization of land endangered by rockfall are in the order of tens of millions of dollars". This is the case for most highways prone to rock falls, because of two factors. First, highway relocation is usually costly, and often involves exposure to other risks. Second, sterilization of a transportation corridor would inhibit access to points along the route, resulting in increased access costs, and possible sterilization of some areas (Lister 1980) along a corridor.

Hungr and Evans (1989) included a lower bound estimate of the annual per capita probability of accidental life loss in Canada due to small-scale rock fall as $1 * 10^{-8}$ based on 13 rock fall deaths in 87 years, and an average population during that period of 15 million people. This underestimates the risk to those Canadians that live in the only province with any rock fall deaths, B.C., and overestimates the risks for Canadians who don't enter B.C.

Fell (1994, p. 266) concluded that in some cases the people living near landslides accept relatively high annual specific risk of loss of their life from natural landslides of 10^{-3}. In contrast, they require annual specific risks of loss of life of not greater than 10^{-5} for engineered structures that are prone to landslide hazards.

Cave (1992) described a codification of a hazard land management program developed in the Fraser-Cheam Regional District of B.C.. He lists "hazard acceptability thresholds" (p. 4) for residential development susceptible to rock fall, debris flood, catastrophic landslide and river flood. The thresholds are more restrictive the higher the density of development and the greater the hazard's threat to life. Cave specifies for "Rockfall: Small-Scale Detachment" (p. 5) that for an area with an annual rock fall return frequency of more than 1:100 all projects from "minor repair" of a damaged structure to "Rezoning (for new community)" are "Not approvable". Cave's lower bound on approvable development is comparable to Fell's (1994) if the probability of loss of life given the event, P(L:T), is on the order of 10^{-3}. The vulnerability of a permanent structure such as a residence is commonly higher than that of vehicles on a highway due to greater exposure time. An individual residence is commonly occupied for more than a third of a every 24 hour period. In contrast a single vehicle passing through a highway cut is exposed to rock fall hazard on the order of 10^{-3} of a 24 hour period. As a result higher rock fall frequencies may be acceptable for highways than residential areas.

Morgan (1991) reviewed voluntary and involuntary risks in western society and compared them to risks from slope hazards. He suggested that society has the right to expect the slope hazard risks associated with a highway would not exceed those of involuntary threshold levels of $1 * 10^{-4}$ to $2 * 10^{-5}$. This is similar to the conclusions reached by Fell (1994) for engineered structures prone to landslides reviewed previously.

Whitman (1984) suggested graphically that engineering projects should have annual probability of failure causing one death of less than about $1.5 * 10^{-2}$. Subsequently, other authors (Hungr et al. 1993 and Salmon 1994, personal communication) have suggested modifications and additions to Whitman's diagram. Hungr et al. (1993) proposed numerical ranges for low, medium and high risk levels based on probability of death and the number of deaths. Salmon (1994, personal communication, B.C. Hydro) discussed acceptable risk levels primarily with respect to dam failures. These limits are applicable to the risk of rock fall on a highway.

Risk assessment is also used in the analysis of the harm that could result from hazardous materials. Ale (1990) outlined the risk policies in the Netherlands and the European Economic Community for hazardous materials. Ale described an upper limit for P(D) almost three orders of magnitude lower than that of Whitman (1984). As discussed by Fell (1994) the acceptable level of risk for natural hazards and those affected by remedial works has not been clarified at this time.

2.3 Rock fall hazard

The definition of rock fall adopted in this study is

> "the detachment of soil or rock from a steep slope along a surface on which little or no shear displacement takes place. The material then descends largely through the air by falling, saltation or rolling. Movement is very rapid to extremely rapid. Except when the displaced mass has been undercut, falling will be preceded by small sliding or toppling movements which separate the displacing material from the undisturbed mass. (Cruden and Varnes 1994, p. 20)

Hutchinson (1988. p. 19) differentiated two types of rock falls, Primary: freshly detached material from parent mass, and Secondary: stones merely lodged upon the rock face. Primary is generally progressive and frequently protracted. It is affected initially by the growth of tension cracks. The final abrupt release commonly occurs through shear failure of the rock mass.

One of the first discussions of rock fall was presented by Bjerrum and Jorstad (1957) in which they reviewed recorded rock falls in Norway. A more recent overview of rock fall literature and research was by Whalley (1984).

Several authors have correlated climatological conditions with rock fall activity. In Norway, the well-marked peak of rock fall activity each spring suggests thawing following ice wedging to be a relevant mechanism instigating rock fall (Bjerrum and Jorstad 1957 and 1968), possibly combined with high water pressures in ice-plugged clefts (Terzaghi 1962). Terzaghi (1962, p. 255) stated "Rock falls involve the intermittent detachment and fall of one or more blocks owing chiefly to the weakening effect of frost wedging and important seasonal temperature changes". Zvelebil (1988) has also correlated rock fall activity from sub-horizontal sandstone beds with monthly climatic conditions in the Labe River Canyon, Czechoslovakia. Culshaw and Bell (1991) reviewed the rock fall history of the James Valley in St Helena. They noted periods of heavy rainfall as the trigger of most rock falls. Hunt (1992) stated that rock failures occur usually during heavy rains with little warning along Highway BR 116 near Rio de Janeiro, Brazil.

Terzaghi (1962) pointed out that high rock fall activity during exceptional wet years can result in a reduction in the number of rock falls before deterioration of the rock produces additional slope failures. He based his conclusions on several hundred years of data presented by Bjerrum and Jorstad (1957) and correlated the high rock fall periods with the temporary glacial advance in Norway during the same period.

The origin of the instability and discontinuities that cause rock falls has also been studied. Bjerrum and Jorstad (1957, p. 5) noted that "After the glaciers had disappeared, the stability of the valley-sides and the fjord-sides was disturbed, and at present, one may say that the stability is not in agreement with the shape of the landscape." Terzaghi (1962) identified slow creep deformation following unloading of glacial ice and shear stresses as being responsible for the development of local joint systems that form unstable blocks. Bawden (1972) briefly reviewed slope failures in south western B.C. including rock falls at Porteau Bluffs on B.C. Highway 99 (figure 5.1). He attributed some of the failures to the instability and ground water conditions following the removal of ice from glacial valleys at the end of the last ice age. Similarly, Gardner (1977) cited glacial unloading, and temperature and groundwater fluctuations as the cause of rock falls and rock slides in the Highwood Pass area of Alberta. Douglas (1980) studied rock fall activity in Antrim County, Northern Ireland. He recognized frost action as causing rock fall but also noted small scale stress changes in the rock face as causing rock falls throughout the year. In the James Valley in St Helena rock fall activity is the result of the removal of vegetation and unfavorable geologic conditions allowing differential erosion (Culshaw and Bell 1991).

Barisone et al. (1991) related the geomechanical characteristics of the rock to the degree of fracturing and then used this parameter to comment on the stability of rock slopes. Shiminzu et al. (1991) modeled the response of jointed rock slopes to earthquake accelerations.

Brawner and Wyllie (1976) and Brawner (1978) described rock fall on railways and noted a reduction in the rock friction angle due to vibrations from trains. Kosar (1979) investigated the rock friction angle and stability of the Porteau Bluffs on B.C.

Highway 99. Douglas (1980), and Gardner (1970 and 1977) studied rock fall magnitude frequency relationships in Northern Ireland and Alberta's Rocky Mountains respectively. Gardner (1970) also included information on diurnal rock fall activity at high altitudes. Clearly, the hazards posed by rock fall are present in many areas and have long been recognized.

2.4 Rock fall risk

The risks resulting from rock fall have also been commented on by many authors. Although they did not identify it as risk, Bjerrum and Jorstad (1957, p. 8) noted "The possibility of damage from rockfalls seems to increase not on account of a greater number of rockfalls, but because of the settlements often spreading out into areas where the danger is greater." Ritchie (1963) studied many aspects of rock falls related to the safe use of highways. This work identified the hazard that rock fall poses to transportation routes through high rock cuts.

Lister (1980) described a land zoning issue between the municipality and the B.C. MOTH regarding the susceptibility of an area at Sunset Beach on B.C. Highway 99 that demonstrated rock fall potential based on the existence of rock fall debris.

Hunt (1984, p 749) stated specifically with respect to roadways that: "Three options exist besides avoiding the hazard, i.e., accepting the hazard, reduce the hazard, or eliminate it. Acceptance is based on an evaluation of the degree of hazard and the economics of prevention." He limited this with the statement "The true economics of this approach, however, depends on the form and magnitude of the potential failure, and assurance that risk is low to moderate." In the case of low to moderate hazards "... where failure is predictable but prevention is considered uneconomical..." the risk may be accepted. Hunt also noted that "Public opinion regarding small but frequent failures of the nuisance type also must be considered."

Hungr and Evans (1988, 1989) and Evans and Hungr (1993) reviewed several rock fall accidents that resulted in fatalities in B.C., including the Just Case.

Nasmith (1980) discussed rockslides, land use and the public's and legal perception of the risks of these events.

As demonstrated, qualitative risk analysis has been applied to rock fall by several authors. Section 4 presents a semi-quantitative methodology for risk assessments.

2.5 Rock fall incidents

A review of rock fall fatalities is included here to demonstrate the extent of the occurrence of this phenomenon.

In some cases victims have stopped their vehicles because of an initial failure or road blockage and then were caught by a subsequent failure. This occurred in the Just Case fatality and the Hope Slide (Mathews and McTaggart 1978). Delays increase exposure time which increases risk. Just was stopped due to heavy snow and traffic delays when his car was impacted. Operationally, it is important to establish where highway users should be stopped in a safe area.

Hungr (1993, personal communication) indicated that similar rock fall-vehicle incidents are presently before the B.C. courts. A judgment on Lewis v. B.C. (1994) has subsequently been released in favor of the claimant. Hungr and Evans (1988 and 1989) and Evans and Hungr (1993) reviewed some other recent and historical rock fall incidents resulting in loss of life and damage in Canada. They also derived a probability of death based on the number of rock fall deaths in an 87 year period and the population of Canada. This gives a lower bound for the risk of rock fall death because the number of people exposed to rock fall hazards is a fraction of the national population.

Eisbacher (1983) reviewed the recent rock fall history of the section of highway between Brunswick Point and Porteau Cove including a rock fall involving three fatalities on February 9, 1969.

Badger and Lowell (1992) summarized the experiences of the Washington State Department of Highways (WSDOT). They stated "A significant number of accidents and nearly a half dozen fatalities have occurred because of rockfall in the last 30 years ...[and] ... 45 percent of all unstable slope problems (landslides, embankments, rock fall, etc.) are rock fall related." (p. 14).

Walkinshaw (1992) presented the results of a survey sent to U.S. state highway authorities for the period 1986 - 1990 regarding costs of remediation and maintenance due to landslides. He discussed the cost of litigation and settlement for damages in cases in California and New York State. Both cases were partially instigated by rock falls, one of which was fatal.

Bjerrum and Jorstad (1967) reported fatalities in Norway due to rock fall and rockslides to be on average two to three per year based on 67 years of records from 1873 to 1940. This average excludes the deaths resulting from two rockslides that fell into water and produced waves that flooded nearby residential areas during the same period.

Culshaw and Bell (1991) noted one rock fall resulting in nine deaths on the Island of St Helena. Wyllie (1993, Golder Associates, Vancouver. Personal communication) acted as an expert witness on a court case in North Carolina arising from a death due to rock fall on a highway. Brawner (1993) reviewed the law in several U.S. states regarding rock fall liability. He also included excerpts from five decisions from North Carolina and

New York State three of which resulted in damages awarded to the plaintiff. Although rock fall fatalities are rare events, they have attracted significant interest. This increased interest is probably the result of litigation resulting from these cases and public demand for greater emphasis on safety.

2.5.1 Just v. B.C.

On January 16, 1982, Just was injured and his daughter, Janet Yvette Dunn killed when a rock fell on their vehicle on B.C. Highway 99. Details of the case and eye witness accounts are included in Hungr and Evans (1989), the Vancouver Province (Berry 1982) and the Vancouver Sun (Smith 1982) newspapers. Just brought an action for damages against the B.C. Provincial Government MOTH based on its responsibility to maintain the highway.

The Supreme Court of Canada decision on Just v. B.C. set a precedent for the responsibilities of governments to "... readily foresee the risk that harm might befall users of a highway if it were not reasonably maintained..." (Cory J. and Sopinka J. 1989, p. 1229).

The following is a brief review of the decisions and arguments resulting from this court case and related appeals. The case was initially heard by the Supreme Court of B.C. by McLachlin J. (1985). She summarized the cause of the rock fall.

> In all probability the fall was caused by the action of tree roots working into natural discontinuities in the rock. The resultant cracks were expanded by successive freeze-thaw cycles. Heavy wet snow settling on the tree, perhaps aided by high winds, caused it to act as a lever on the rock. (p. 350)

McLachlin J. decided in favor of the province of British Columbia. Her argument for this decision was based on the reasoning that

> Before the issue of negligence can arise, it must be determined whether the conduct complained of falls within the category of acts for which the governmental bodies may be held liable. This category concerns conduct which is "operational" as opposed to conduct which falls within the realm of "policy" and which is not reviewable by the courts. While ...
>
> In this case the conduct at issue fell within the realm of policy. A decision of the rock scaling crew as to what slopes to inspect and scale is a planning decision and their choice of when and where to inspect and do remedial work is essentially a matter of deciding where the limited resources available within the budget can best be applied. The crew has virtually and absolute discretion as to when and where it works. It creates the standards and it determines their enforcement so that there are no standards to which it is required to work or against which its conduct can be evaluated apart from those it sets itself. Nor did the fact that the crew, as a body making the decision, worked in the field prevent the decision from being a matter of policy. Higher policy-making organs of the government may delegate their policy-making powers to those

> charged with dealing with problems on a day-to-day basis. (McLachlin J. 1985, p. 349).

The case was appealed by Just, and as a result, heard by the Court of Appeal of British Columbia by Justices Taggart, Hinkson and Macfarlane (1986). They agreed with the trial judge and dismissed the case.

The case was subsequently appealed to the Supreme Court of Canada (S.C.C.). For the majority Cory J. (Cory J. and Sopinka J. 1989) stated that

> The province owes a duty of care, which ordinarily extends to their reasonable maintenance, to those using its highways. The Department of Highways could readily foresee the risk that harm might befall users of a highway if it were not reasonably maintained. That maintenance could be found to extend to the prevention of injury from falling rock (p. 1229).

With respect to the lower courts claim that MOTH could not be questioned on matters of policy the S.C.C. found that

> Here [the Just Case] what was challenged was the manner in which the inspections were carried out, their frequency or infrequency and how and when trees above the rock cut should have been inspected, and the manner in which cutting and scaling operations should have been carried out. In short the public authority had settled on a plan which called upon it to inspect all slopes visually and then conduct further inspections of those slopes where the taking of additional safety measures was warranted. Those matters are all part and parcel of what Manson J. described as "the product of administrative direction, expert or professional opinion, technical standards of care". They were not decisions that could be designated as policy decisions. Rather they were manifestations of the implementation of the policy decision to inspect and were operational in nature. As such they were subject to review by the Court to determine whether the respondent had been negligent or had satisfied the appropriate standard of care.
>
> To proceed in this way is fair to both the government agency and the litigant. Once a duty of care that is not exempted has been established the trial will determine whether the government agency has met the requisite standard of care. At that stage the system and manner of inspection may be reviewed. However, the review will be undertaken bearing in mind the budgetary restraints imposed and the availability of personnel and equipment to carry out such inspections. (pp. 1245 - 1246)

As a result of the S.C.C. findings they ordered that

> a new trial must be held to determine whether the respondent [the B.C. government] had in all circumstances met the standard of care that should reasonably be imposed upon it with regard to the frequency and manner of inspection of the rock cut and to the cutting and sealing operations carried out upon it (p. 1246).

In a dissenting judgment one of the S.C.C. justices to hear the case, Sopinka J. stated that the "Respondent had the power to carry out inspections but was under no duty to do so." (p. 1229).

In accordance with the findings of the S.C.C., Justice Donald of the B.C. Supreme Court (1991) reviewed the case and found

> The defendant failed to meet a reasonable standard of care in not conducting a climbing inspection before the accident. I conclude therefore that the defendant is liable to the plaintiff for damages in negligence.

As part of Justice Donald's decision he ordered the government of B.C. compensate Just to the sum of approximately $1.0 million. This court case contains most of the technical information related to the stability of the rock face and the conditions that resulted in the injury and death to Just and his daughter respectively.

At least two articles have been written regarding the precedent set in this case. Both Klar (1990) and Woodall (1992) focus on the S.C.C. decision with respect to its definition of a policy and an operational decision.

It was determined during the B.C. Supreme Court trial that based on the testimony of expert witnesses.

> Engineering standards call for a climbing inspection when the slope presents significant signs of instability. .... Physical evidence of the tree in a fallen position and the cavity from which the boulder was pried loose leads to the conclusion that a competent rock engineer, having climbed the slope, would have readily seen how the tree was rooted in the rock and perceived the hazard. Especially dangerous trees are removed separately from a general scaling program. That is what should have happened in this case. (Donald J. 1991, p. 224)"

This study will investigate whether it is reasonable to expect that engineering standards of the level specified by Donald J. (1991) are appropriate based on the risk of this type of event.

2.6 Mathematical modeling

Several mathematical and computer automated rock fall trajectory models exist in the literature. Ritchie (1963) was perhaps the first to quantify the behavior of falling rocks. He studied the insitu behavior and mechanics of rock falls in field tests and derived expressions for the trajectory of falling rocks. Azzoni et al. (1991) also completed field work on rock fall movement. They quantified the parameters that control rock fall trajectory, including the coefficient of restitution of a bouncing rock, the rolling friction coefficient, the type of movement and the kinetic energy of the fall for different rock types and slope conditions.

Numerous recent models have been developed for use on a personal computer. Bozzolo et al. (1988) and Spang and Rautenstrauch (1988) describe mathematical rock fall modeling compared with field data. Hungr and Evans (1988, 1989) developed

ROCKFALL a modeling program with detailed velocity analysis. The Colorado Rockfall Simulation Program (CRSP) was developed by Pfeiffer (1990) and is now used by several agencies, notably the WSDOT (Badger and Lowell 1992). The WSDOT uses the CRSP to design tunnel portal extensions, rock fall ditches and fences. Duffy (1992) described some of the physics used to calculate rock fall energy.

2.7 Rock fall hazard analysis systems

Several authors have proposed rock fall or slope stability hazard and risk rating systems. Hunt (1992) described slope failure risk mapping for highways. Hunt identified two options for addressing slope problems: provide complete stability of all cuts and fills or accept some failure risk and stabilize areas with potential for failures of serious consequence. His methodology is entirely qualitative with a rating scheme scale of 1 as very high risk to 5 no risk where rock fall is considered a 3 or moderate risk. Romana (1985, 1988, 1991) has also formulated a Slope Mass Rating (SMR) based on Bieniawski's (1976) widely accepted RMR. Cancelli and Crosta (1993) presented a risk mapping technique for rock fall that assigns relative numbers to the risks associated with different conditions with respect to the land use and rock fall characteristics.

The Rockfall Hazard Rating System (RHRS) (Pierson et. al. 1990) was developed by the Oregon State Highway Division for the ranking of hazards due to rock falls on highways. This system was adopted for this study because it heightens awareness of the many factors that contribute to the rock fall activity of an area. In addition, it allows the correlation of the risk analysis methodology developed in this research with a presently accepted rock fall analysis system. The following is an overview of the RHRS.

2.7.1 Oregon State Highway Rockfall Hazard Rating System

The Rockfall Hazard Rating System (Pierson et al. 1990) presented a methodology for managing rock fall prone areas of transportation routes. The RHRS has been used by the WSDOT since 1988 (Pierson et al. 1990). A pilot project in the northwest part of the state was initiated in 1989. Phase 1 rated 39 sites, phase 2 provided remedial designs and cost estimates. In 1990 WSDOT spent $250,000 to begin work on the list of 39 sites. In 1992 work continued on the 39 sites. Since the pilot study a 10 mile length of Interstate in the northwestern portion of the state has been priority ranked. In B.C. MOTH has adopted the RHRS (Don Gillespie 1993, personal communication) and has begun rating its routes.

The RHRS consists of five parts: preliminary rating of all slopes, detailed rating of all hazardous slopes, preliminary design and cost estimates for the most serious sections, project identification and development, and annual review and update (Pierson et al. 1990). The following is a brief discussion of a few of the aspects of the RHRS significant to this research.

2.7.1.1 Slope inventory

The slope inventory should be completed with the assistance of the maintenance staff most familiar with the highway's rock fall history and maintenance record. Several questions should be answered. Where are the rock falls occurring? What is the frequency of rock fall? At what time of year are rock falls most frequent? What is the volume of each rock fall? What is the type of rock falling? Where do the rock falls come to rest? What is the accident history? What are the rock fall causes? What is the frequency of ditch cleaning and road patrol? Finally, what are the costs of rock fall damage and cleanup? (Pierson et al. 1990, p. 7)

2.7.1.2 Preliminary rating

The purpose of the preliminary stage is to reduce the number of slopes that should be investigated in detail. Sites are classified as high, moderate and low estimated potential for rock on the roadway and are summarized in Table 2.1.

Table 2.1 Preliminary Rating System (after Pierson et al. 1990)

Class	A	B	C
Criteria			
Estimated potential for rock on roadway	High	Moderate	Low
Historical rock fall activity	High	Moderate	Low

High potential results from large rocks, large quantity of rock per event, large amounts of rock available and low ditch effectiveness. High historical activity reflects high frequency of recorded rock fall on the highway, of a large quantity, consisting of large rocks, and high frequency of clean up.

2.7.1.3 Detailed rating system

The detailed rating of each cut is the sum of 10 independent evaluations of the rock cut's characteristics. These include scores for vertical slope height, ditch effectiveness, average vehicle risk, available proportion of decision sight distance, roadway width, block size or quantity of rock per fall, climate and water conditions, and rock fall history. The geological characteristics of a cut, consists a choice of ratings depending on whether discontinuities or differential erosion causes the most rock falls. A cut can be rated based on its discontinuity orientation and continuity and the rock friction, or on the existence of differential erosional features and the relative rates of differential erosion.

The rock fall history, and the block size/quantity ratings are the only portions of the survey that reflect the remediation effort employed on a rock cut. The ditch effectiveness and roadway width can also be improved to lower the rating but the remaining rating categories can only be subtly reduced without re-routing the roadway.

2.7.1.4 Decision sight distance score

To introduce a factor that reflects the amount of time a driver has to react if they encounter fallen rock on the highway the RHRS used the percentage of the decision sight distance, PDSD. The PDSD of a road is 100 * ASD/DSD, where ASD is the actual sight distance and DSD is the decision sight distance. The ASD is the greatest distance along a roadway that a six inch object is continuously visible from 1.0 m above the road, the height of a driver's head in a low profile vehicle. The DSD is the distance traveled for a driver to have time (about 10 seconds) to make a complex decision and act on that decision (AASHTO 1990). The DSD is longer than the stopping distance for a given speed so that if required a driver can stop their vehicle within the DSD. As a result the DSD is dependent on the speed of the vehicle. Table 2.2 contains the required DSD for a range of highway speeds.

Table 2.2 Decision sight distance versus speed (adapted from AASHTO 1990)

Posted speed limit (km/h)	50	60	70	80	90	100	110
Decision sight distance (m) (DSD)	140	170	200	230	270	310	330
Time (s)	10.2	10.2	10.2	10.2	10.9	11.2	10.8

2.8 Rock fall hazard mitigation techniques

Rock fall hazard mitigation techniques can be divided into three basic methodologies: minimize the hazard through design and construction, remediate natural or excavated slopes, and inhibit rock fall movement from posing a hazard to the public. The second and third methods were identified by Bjerrum and Jorstad (1957, p. 19). Although not feasible for small failures, Bjerrum and Jorstad also noted that crack width monitoring can be used to identify when the probability of large rock falls increases.

Initially, it may be possible when designing and constructing an engineered slope to minimize the hazard from rock fall by utilizing specific design criteria and excavation techniques. Piteau and Peckover (1978), Hoek and Bray (1977), Goodman (1989), have presented techniques and criteria for cut designs based on the characteristics of the rock's structural discontinuities and the excavation geometry. Excavation techniques included minimizing blast damage, staged excavation and ripping. The use of catch berms or benched slopes to minimize rock fall hazard is common but at least one agency is reconsidering their benefits. The WSDOT no longer utilize mid slope catch berms for two reasons (Badger and Lowell 1992). First, the berms fill with rock and are difficult and costly to clean. Second, they increase the horizontal component of rock fall velocity increasing the likelihood of the fragment reaching the traffic pathway.

When considering natural slopes this first approach is not available. However, it is commonly possible to reduce or minimize the number of rock falls by removing unstable rock, reinforcing the slope, and preventing the processes leading to rock fall by reducing infiltration and improving drainage (Bjerrum and Jorstad 1957, Peckover 1975, Peckover and Kerr 1977, Fookes and Sweeney 1976, Piteau and Peckover 1978).

Third, attention can be focused on stopping falling rocks reaching the roadway since it has long been recognized that not all rocks can be prevented from falling (Bjerrum and Jorstad 1967). Ritchie (1963) recommended using structures to inhibit the free movement of rock falls down slopes and containment areas at the base of the slope to stop rocks from reaching the roadway. Bjerrum and Jorstad (1957) mention diversion walls and coverings or tunnels and the use of walls and walls and fences. Piteau and Peckover (1978) added other techniques including warning systems and rock fall sheds. Andrew (1992) investigated the efficiencies of three specific types of rock fall barriers: tire attenuators, flexpost fence, and geosynthetic-reinforced impact walls. The CRSP (Pfeiffer and Higgins 1990) was used to evaluate the effectiveness of these rock fall attenuators. Hearn et al. (1992) described the procedures and results from testing "flexpost" rock fall fence developed by the California Department of Transportation.

Duffy (1992) described the testing and effectiveness of two types of European manufactured flexible wire rope rock fall nets in California.

Vegetation is considered to inhibit rock saltation or bouncing and rolling (Lister 1980, Hungr and Evans 1989, and Evans and Hungr 1993) on longer slopes and at the base of scree slopes but vegetation has been identified as a cause of rock fall (Terzaghi 1962, Bjerrum and Jorstad 1968 and Oliver *in* Donald J. 1991) on steep slopes. On some slopes vegetation will act as both a rock fall inhibitor and rock fall cause. The relative importance of these two influences should be investigated before action is taken to remove or encourage vegetation on a slope.

Badger and Lowell (1992) presented an overview of rock fall hazard management and prevention in Washington State. Since 1963 the WSDOT has utilized the rock fall ditch design developed by Ritchie (1963). They are also proponents of controlled blasting, horizontal rock drains, ditch widths related to slope height and slope angle, rock fall protection fences, wire mesh slope protection, gabion barriers, and rock debris barriers. The WSDOT also scales and trims potential or active rock fall zones and completes face treatment with shotcrete. In frequent rock fall areas WSDOT uses rock sheds, tunnel portal extensions and rock patrols.

Fourth, monitoring may be used to warn of impending rock fall. Crack and displacement monitoring included the use of surveying and extensometer was suggested by Bjerrum and Jorstad (1957). The identification and large number of possible rock falls combined with the rapidly changing stability of relatively small volumes of material make monitoring impractical in most cases.

2.9 Conclusion

In some mountainous terrain, large potential rock fall source areas are present along roadways. These large areas combined with the limited size of individual potential falls results in a multitude of potential rock falls. In addition, the small size of most rock falls results in the stability of individual blocks changing rapidly due to small changes in the stability controlling parameters. As a result, the timing of most rock falls cannot be predicted. These factors make the application of deterministic identification and analysis impractical. This is not to say that specific potential rock falls cannot be identified and remediated. It does, however, suggest that rock fall conditions range from those that lend themselves to deterministic techniques to those that can best be investigated and analyzed using probabilistic methods. In conclusion, it is apparent that in some cases rock fall can best be analyzed as a probabilistic process rather than a deterministic one.

3.0 Risk analysis

The Canadian Standard Association (CAN/CSA 1991) presented a generic risk analysis sufficiently general to be applicable to many different situations. The following is a discussion of the risk analysis techniques applicable to rock falls on highways

3.1 Analysis methods

There are several forms of risk analysis each suited to a different type of process. "Methods of Analysis of Engineering Systems" (CAN/CSA 1991, pp. 21 - 24) was chosen for the quantification of risk posed by rock falls on a highway. A "Pathway Analysis" frame work could also be used.

All risk analysis should include six stages in the following order (CAN/CSA 1991, p. 15):

1. scope definition
2. hazard identification
3. risk estimation
4. documentation
5. verification
6. analysis update

3.2 Risk estimate

The output from a full risk analysis is expected to contain estimates of one or more parameters. Those of interest in the rock fall highway situation are (CAN/CSA 1991, pp. 14 - 15):

i) individual risk to members of the general public
ii) societal risk to the general public
iii) occupational risk among work force

Occupational risk would include the risk to highway maintenance workers and scaling crews. Scaling is a specialized, high risk profession and, as such, will not be addressed in this research. Occupational risk is not considered specifically in this analysis but it can be derived from i) and ii). The risk to highway maintenance personnel working in a cut can be considered using the methodology for a stationary vehicle and a falling rock (section 4.5.1). The risk to highway personnel whose occupation includes the use of the highway is similar to that of a frequent user such as a daily commuter discussed in section 5.4.4.

3.3 Criteria for risk analysis detail

At the outset, consideration should be given to the risk analysis requirements. CAN/CSA (1991) suggests that level of analysis be related to the severity of the outcome of the hazard by using Table 3.1 (CAN/CSA 1991, p. 22).

Table 3.1 Frequency severity matrix and action guide

Frequency	Severity			
	Catastrophic	Major	Minor	Negligible
frequent	A	A	A	C
probable	A	A	B	C
occasional	A	B	B	D
remote	A	B	C	D
improbable	B	C	C	D

A - detailed quantitative
B - semi quantitative
C - qualitative
D - not required

The application of this table requires quantification of the various relative terms. In the case of rock fall a catastrophic event might be the impacting of a large rock fall on a bus that then fell onto the B.C. Rail train tracks below, derailing a passenger train which plunged into Howe Sound. Negligible could be a short traffic delay. Frequent, could be every time there are freezing temperatures or a significant rainfall. Remote, could be the one in hundred year flood event which is commonly subject to a detailed quantitative modeling, but only when its impact could be catastrophic. Therefore, frequent would be in the order of 10 per year, probable: 1 per year, occasional: 1 in ten years, remote: 1 in a hundred years, and improbable 1 in a thousand years. This is similar to Cave (1992)

This study considers the Just Case to represent major severity (one death and one injury), and considering one death in the 37 year history of the Argillite Cut the frequency is occasional to remote. Therefore a semi-quantitative risk analysis is justified.

3.4 Forms of risk

Risk is expressed in several forms depending on the entity at risk. As defined in section 2.2 risk can refer to expected losses of lives, persons injured, property damaged, or economic activity disrupted. As a result the following expressions of risks are used (CAN/CSA 1991, p. 18).

i) frequency of mortality or morbidity

ii) frequency versus consequence, sometimes known as f - n curves for societal risk

iii) statistically expected loss rate

iv) distribution of risk damage levels

For natural hazards, engineering projects and the process industries the two most commonly used risk parameters are the probability of an individual death, PDI (Morgan 1991 and 1992, Ale 1991) and the probability of death to the exposed population for a specific time period, P(D) (Whitman 1984, Salmon 1994, Ale 1991). PDI is a form of statistically expected loss rate and P(D) is a frequency of mortality. Calculating these two parameters for rock falls on highways makes it possible to compare rock fall risks to other published risk levels for natural hazards, engineering projects, and specific activities and occupations.

4.0 Rock fall risk analysis

The following is a risk analysis methodology for rock falls on a highway. It proceeds through the six stages listed in section 3.1. The calculation of risk to individuals and the risk to the general public are specified in terms of a return period for a rock fall accident and the probability of an individual being effected by a rock fall. The level of investigation described is semi-quantitative but the methodology can be enhanced or simplified for more or less rigorous studies. Enhancements that would make the methodology detailed quantitative are noted throughout the study.

4.1 Scope definition

The scope definition is separated into five elements that should be completed at the start of the investigation (CAN/CSA 1991, p. 17).

1. The problem originating the risk analysis should be described and the objective of the risk analysis formulated based on the main concerns. Rock fall is an unpredictable natural process that occurs without notice from locally unstable rock faces and slopes. When it occurs in the proximity of a highway the falling rocks may impact the highway and the highway users. In approximate order of significance and cost the main concerns are then loss of life, injury, traffic delays, damage to the highway, highway maintenance costs and damage to vehicles. There are two objectives of this analysis. One is to quantify the risks along the highway to facilitate informed allocation of limited resources to remediate the areas with high risk. The second is to compare the risk associated with rock fall to other risks accepted voluntarily or involuntarily by the public.

2. The system being analyzed should be defined. This includes:

i) A general description of the rock fall highway system location, importance of the route and the reasons for completing a rock fall risk assessment.

ii) A definition of the boundaries of the system both physical and functional. This comprises the length and height of the rock fall source area, and the length of the highway exposed to rock falls.

iii) A description of the environment. This includes climatic information regarding the rainfall and snowfall, annual temperatures, and the number of freeze-thaw cycles per year. It should also contain the slope geometry, ditch effectiveness, road width, visibility, engineering geology of the rock fall source area, rock fall prevention measures, and the vegetation of the area.

iv) A definition of all the flows and influences that cross the physical and functional boundaries. This includes the type and speed of traffic; the daily, weekly and seasonal usage patterns. The influences that effect the area include physical and chemical weathering, climatic conditions, anthropogenic modification and biological activity. Physical and chemical weathering includes ratcheting of cracks (Bjerrum and Jorstad 1968, Cruden et al. 1993) and chemical degradation of minerals. Climatic consequences are erosion, wetting and drying, precipitation, freeze-thaw and snow loading. Anthropogenic effects include excavation, scaling, rock anchoring and bolting, shotcreting, deforestation and the introduction of foreign vegetation. Biological activity includes natural vegetation and wild life growth and usage patterns. Commonly, the most detrimental form of biological activity is disturbance by root growth (Bjerrum and Jorstad 1968) which may result in loosening of the rock mass and increased groundwater infiltration.

v) A definition of the operating conditions covered by the risk analysis and any limitations. Commonly this encompasses all climatic and traffic flow conditions but may only consider averages of these rather than the extremes. External influences such as earthquakes, tidal waves and floods that may trigger rock falls may also be excluded. Rock fall risks resulting from external events should be considered part of the hazard posed by the external event.

vi) Details of all technical, environmental, organizational and human circumstances that are relevant. This includes the rock fall and remediation history of the area; preventative measures to minimize exposure through signage, warnings and road closures.

3. The assumptions and constraints governing the analysis should be stated. These would include assumptions based on rock fall probabilities, traffic flows, incomplete information or interpretations of data.

4. The decisions that have to be made, the criteria for these decisions, and the identity of the decision makers should be established at the onset of the investigation. Decisions resulting from this process include the determination of whether action is warranted based on the magnitude of the risk. If action is required, warnings, remedial measures, temporary closures and realignment of the highway might be adopted. The decision-making process commonly falls to a highway or transportation department of the government. In some jurisdictions this may include the consultation of specialists.

5. Documentation requirements of the risk analysis plan is included in detail in CAN/CSA (1991).

4.2 Hazard identification methodology

Several methodologies suggested for hazard identification (CAN/CSA 1991) are appropriate for rock falls. This research utilizes three comparative methods for rock fall hazard identification: 1) a checklist of conditions that may produce rock fall that will result in hazards to a roadway; 2) hazard indices that rank hazards based on the extent to which specific conditions are present (Pierson et al. 1990); and 3) review of historical information to provide examples of rock fall incidents and the range of outcomes. Generally, methods that stimulate foresight, including hazard and operability studies, and failure mode and effect analysis, (CAN/CSA 1991, p. 23) are not useful for rock fall hazards identification, because rock fall does not require process and failure analysis of a system.

Fault tree logic (CAN/CSA 1991, p. 30 - 32) is appropriate for rock fall hazard identification, and is described more rigorously in section 4.4.4.

The course of action for each hazard should be considered during the preliminary evaluation of the hazard. If severe hazards are defined, corrective action may be taken at this point. If not, further detailed analysis or the decision to end analysis here should be considered.

In the case of rock fall hazards, identification is simplified due to the specialization of the subject. However, the hazards posed by rock fall have several forms. First, there is the hazard to moving highway traffic of being impacted by a rock. Second, a stationary vehicle could be impacted by a rock. Third, there is a hazard that a moving vehicle could hit a rock that previously fell on the road. Fourth, a rock fall could block traffic flow causing costly delays and diversions. Fifth, damage and highway maintenance costs could be caused by a rock fall. Additional hazards that might be considered are related to non-conventional highway users including pedestrians or cyclists and highway maintenance workers or contractors. The magnitude and duration of a rock fall will affect the nature of the hazard. The larger and the longer the duration of a rock fall, the greater the hazard.

4.3 Risk estimation

Risk estimation encompasses several topics. These include frequency and consequence analysis, selection of either qualitative or quantitative analysis methods, determination of the required data, statement of assumptions and rationale of the previous stages, and estimation or the risks with their sensitivity or uncertainty. Where the data is not available, information of a representative or generic nature or expert judgment should be used.

A sensitivity analysis should be included in a detailed quantitative risk assessment. In a sensitivity analysis the parameters to which the risk analysis is sensitive are identified, and the uncertainty of these parameters expressed. For less detailed analysis, a sensitivity analysis may not be applicable due to the uncertainty in the input parameters.

4.3.1 Frequency analysis

A frequency analysis investigates the hazard sources to determine the likelihood and nature of each event. Using historical data, it determines the frequency with which rock falls have occurred in the past and then makes a judgment as to the frequency of their occurrence in the future or estimates event frequency using a technique such as event tree as described in section 4.4.4.

The rock fall frequency is commonly difficult to assess. Gray (1972) cited several techniques he and other authors used for measuring rock fall activity in natural areas. These may or may not be appropriate in areas of relatively low rock fall frequency or where the measurement methods interfere with human activity or vice versa. Along highways several other information sources may be employed.

Rock fall frequency can be assessed by inspecting the ditch and disposal areas for rock fall material. The volume of rock fall material removed during scaling and ditch cleaning is indicative of rock fall activity. This information may be available from maintenance operations in units of loads hauled and may be confirmed or augmented by surveys of the ditch and disposal areas before and after cleaning. It may be possible to date the material by its freshness and vegetation and lichen growth (Gray 1972). In some cases modeling of rock slope retreat may also be possible (Gray 1972).

The two additional methods of rock fall frequency estimation used in this research are rock fall-impact asphalt-damage mapping and documented rock fall activity. These two methods were chosen because of the availability of information and the applicability to this analysis.

4.3.1.1 Rock fall-impact asphalt-damage mapping

Rock falls commonly sear asphalt-surfaced roads. The number of sears is representative of the number of rock falls that have hit the roadway. There are two advantages to this method of rock fall frequency analysis. First, only those rocks that reach the road are included. Therefore no prediction of rock fall trajectory is required to determine the number of rocks that bounce over the road or fall into the ditch from the total number of rock falls. Second, the method does not require an extended observation period. The mapping of rock fall impact-marks can be completed in a period of hours or days. The date of the last re-paving of the road will allow the calculation of the frequency of rock falls since that event. The event frequency can then be updated months or years later by comparing the results to previous surveys.

There are several limitations that should be considered when using this information. Damage to the asphalt can occur from numerous sources including impacts, weathering, mechanical damage, consolidation, creep, and construction flaws. Rock fall-impact asphalt-damage is characterized by isolated, sharply-defined, angular to sub-angular depressions in the asphalt surface. Rock fall impacts can be distinguished from other damage based on these characteristics. Mechanical damage by the teeth on the bucket of a front end loader or other heavy equipment used for the removal of rock fall debris is present in most areas of extensive rock fall impacts. This damage can be distinguished from rock fall impact by the close spacing of shallow, parallel, linear markings or scratches. In some cases this damage will result in isolated depressions but their elongated arcuate character and narrowing and shallowing terminations identifies their anthropogenic origin. Concrete roadways require higher energy impact before damage is visible.

It is possible that some rock fall events will not damage the asphalt due to their trajectory or size. Rolling rocks may present a hazard but leave no impact mark. Similarly, small rocks may not damage the road but still pose a hazard to vulnerable areas of vehicles. In many cases a number of impact marks may have been produced by a single event. This type of event may be interpreted from evidence of the source area of the rock fall and the number of rock falls versus the number of rock fall marks adjusted.

4.3.1.2 Documented rock fall activity

Documentation of rock fall activity is commonly available for most roads with a history of rock fall activity. Often the best source is highway maintenance records. These may indicate rock fall locations, volumes and times but seldom include small rocks less than 15 cm in diameter (Bartle 1993, personal communication). Complete rock fall records are rare due to the low population densities in rock fall areas; the remoteness of the locations; the lack of reporting of small events by the public, police or maintenance workers; and the personnel or monitoring costs that would be associated with data collection. The relative significance of impacts is often difficult to assess because of the lack of reporting of insignificant impacts. Impacts that are not considered life threatening or significantly damaging usually go unreported.

Remediation efforts are reflected in the rock fall history. For this reason, it is important to maintain complete records of rock falls before and after the installation of remediation works to properly assess the reduction in rock fall activity and the effectiveness of the measures.

The frequency of fallen rocks being encountered can be estimated from the number of rock falls and the time it takes highway maintenance, other agencies or the public to remove them. Additional information may be available in police records, accident records and insurance claims.

4.3.2 Failure mechanism

It may be possible to correlate rock fall frequency with external conditions thereby refining the frequency analysis by producing conditional frequencies. The fall mechanism is commonly controlled by external conditions. For any fall, some change in the static equilibrium of the rock is required to instigate movement. The occurrence of a rock fall is commonly controlled by climatic and biological events because these produce the most rapidly changing forces acting on a rock. Possible rainfall-triggered mechanisms include rainfall infiltration increasing pore pressures, and erosion. Loosening due to stress release, freeze-thaw, chemical degradation of the rock mass, root growth, leverage by roots of vegetation moving in high winds, and temperature fluctuations may also trigger movement. Of these, precipitation is the most variable and therefore most commonly identified as causing a rock fall.

When it is possible to distinguish which event caused a given rock fall, an event tree analysis described in section 4.4.4 can be utilized to assess the risk given the occurrence of an instigating event.

4.3.3 Vulnerability

As described in section 2.2, vulnerability has three components. When considering the vulnerability of death from rock fall the three components are spatial occupancy of location effected by a rock fall, the time of occupancy with respect to time of the fall, and whether a fatality results. Vulnerability is dependent on several factors depending on which type of vehicle rock fall interaction is considered and the expression of risk. These factors include a vehicle's speed and length, the length of the driver's decision sight distance, the traffic volume, the length of the rock fall area, the length of the road effected by a rock fall, the number of occupants in a vehicle, and the type of vehicle.

Several aspects of traffic volume should be considered. It is common to have low and high traffic volume cycles with daily, weekly and annual periods. Traffic volume measurements or estimates can be obtained from transportation authorities or by monitoring traffic flow. In addition, traffic volume influences velocity: as volume increases, velocity decreases. Commonly, available traffic statistics will not quantify all the effects of traffic flow patterns.

As recognized in section 2.3, climatic conditions including snow, freezing temperatures and rain may instigate rock falls. These conditions also diminish driving visibility which reduces a driver's sight distance and therefore their potential to avoid fallen rocks. These same conditions may increase usage of the roadway by skiers accessing mountainous terrain or people returning from vacations due to poor weather. Detailed traffic volumes are seldom available and therefore climate and traffic usage are commonly assumed to be independent.

Not every rock that strikes a vehicle will cause an injury or death due to the variation in how the rock impacts the vehicle and the energy of the rock. Smaller rock falls must impact a smaller target portion of a vehicle to cause injury or death. Larger rock falls only have to impact a portion of the vehicle in order to cause death, injury or disable the vehicle sufficiently to result in harm to the passengers. The greater the number of occupants per vehicle the higher the risk of death because more people are exposed to the hazard and the vulnerable area of the vehicle is increased. The frequency of high occupancy vehicles such as buses is therefore significant. It may be possible to quantify the number of buses using a highway from scheduled bus usage and information from bus charter firms.

Vehicle speed has two effects on vulnerability. Higher vehicle speeds result in lower exposure time to falling rocks but it also reduces the driver's ability to stop or avoid fallen rocks on the road thus increasing the spatial, temporal and mortality components of vulnerability for this case. At one extreme, traffic stopped in a rock fall area due to previous falls, or other incidents increases the exposure time of the stopped individuals by several orders of magnitude. At the other extreme high speed travel reduces the driver's ability to respond to unforeseen conditions on the road including fallen rocks.

Uneven traffic flow develops on rock fall prone roadways for a variety of reasons. These highways typically provide access through mountainous terrain with high construction costs. To minimize costs, the highways are commonly narrow, winding, single-lane roads with few passing areas and steep grades. They are often the sole transportation artery to an area and are often considered scenic routes due to the mountainous terrain. This results in both tourists who travel slowly and through traffic which desires fast access, simultaneously utilizing the route. In addition, the variety of vehicles including transport trucks, under-powered recreational vehicles and passenger automobiles have a wide range of acceleration capabilities. The winding nature of the highways requires frequent deceleration and acceleration. All these factors cause uneven traffic flow with groups of faster vehicles following slower ones. This increases the population exposed to rock fall hazard for two reasons. First, the larger the number of vehicles in a group accelerating and decelerating around curves and up and down steep grades, the lower the average velocity which increases the exposure time. Second, closely spaced vehicles are at a greater risk of collision between the vehicles in the event of a rock fall affecting one of a group of vehicles.

Traffic delays due to previous failures, or other incidents can increase exposure duration. The timing of the exposure with respect to rock fall activity can be controlled by road closures and warning systems that may eliminate or reduce usage during hazardous periods. Warning systems that induce drivers to reduce their vehicle speed and proceed cautiously during periods with increased rock fall can lessen the probability of hitting a fallen rock. The probability of impacting a fallen rock is usually significantly greater than the probability of being hit by a rock. Reducing vehicle speed allows drivers more time to respond to a fallen rock which reduces the probability of an impact. Concurrently reducing vehicle speed increases exposure to falling rocks but the increase in the lower probability event seldom exceeds the reduction in the higher probability event.

4.3.4 Consequence analysis

"Consequence analysis involves estimating the impact on adjacent people, property or the environment should the undesired event occur" CAN/CSA (1991, p. 23). In this study the undesired event is a rock fall on the highway. Consequence analysis consists of estimating the probability of people being in the proximity of a rock fall when it occurs, and how they will be effected by the rock fall. Knowledge of the mechanism that causes rock falls and the trajectory of the rock could be used to calculated the effect of the fall at any distance from the source at any time.

Consequence analysis should be based on a specific rock fall area selected. Every series of consequences resulting from a rock fall should be described. This may take the form of a fault tree described in section 4.4.4. All measures to minimize or influence the consequences of rock falls should be considered, including rock fall catchment systems, road width, traffic volumes and others. The criteria used to identify the consequences of a rock fall must be given. These criteria included recorded outcomes, outcomes to an average vehicle, or worst cases scenario. Generally, rock fall has immediate identifiable results but for some rock fall vehicle related injuries the consequences may only arise after some period. As a result, this analysis should consider both immediate and longer term consequences of rock falls.

Consequence analysis has not been used to derive a quantitative risk but several aspects of rock fall can be considered using consequence analysis. The following is a more detailed description of some of these.

4.3.4.1 Rock fall energy and size

The energy of a rock fall is a function of its mass and its velocity. The size of the rock particle involved in a rock fall will have a significant effect on the hazard of the event. It is expected that the rock fall particle size distribution generally has many small, and few large falls. The particle size may depend on the discontinuity spacing of the rock mass and the weathering characteristics.

The energy of a given rock fall particle depends on several factors. The frequency of low-energy rock fall particles is often more than an order of magnitude greater than the frequency of higher energy rock falls. Gardner (1970) presented rock fall frequency magnitude data that suggests a distribution skewed by more large events. Although he recognized that "the very small-scale events had a low observed frequency, perhaps a result of these small rockfalls failing to attract the observer's attention" (pp. 18 - 19), Gardner (1977) estimated that in the Highwood Pass, Alberta, rock falls of less than 10^{-3} m^3 occurred more than 100 times more frequently than rock falls greater than 1 m^3. Similarly, Douglas (1990) plotted the rock fall frequency-magnitude relationship of a Northern Ireland basalt as approximately negative exponential. The exact frequency magnitude relationship varies with the rock properties, and climate but all the data reviewed by Whalley (1984) shows it is approximately negative exponential. A low energy event must impact a more vulnerable portion of a vehicle to disable it, while a high energy rock could disable a vehicle if it impacted anywhere on a large portion of a vehicle. In addition, a small fallen rock will have little effect on a moving vehicle while a large rock on the road could seriously damage a moving vehicle.

4.3.4.2 Trajectory characteristics

The trajectory will affect the distance a rock travels and therefore the area of hazard within the limits of the roadway. The greater the area of hazard the longer the exposure to risk of impact. The trajectory of a rock fall will depend on several parameters most of which are site specific and highly variable. The strength and the modulus of elasticity of the rock and the material it impacts on its descent affects the rock's path. The roughness of the slope and the shape of the rock will also influence the rock fall. Each impact affects the kinematic and potential energy and the angular momentum of the rock during its descent.

The use of rock fall fences can control the trajectory and when used their affect should be considered in the hazard assessment.

4.3.4.3 Rock fall vehicle interaction

The nature of the rock fall-vehicle interaction will greatly influence the amount and type of loss or damage. Three combinations of interaction have been previously identified, moving vehicle/falling rock, moving vehicle/stationary rock, and stationary vehicle/falling rock. Within these categories the size of the rock, the number of passengers in the vehicle, the speed and type of vehicle and the rock will affect the risk of the interaction.

Several factors affect the result of a falling rock impacting moving or stationary vehicles. At one extreme the impact could so severely damage a car that the occupants are killed immediately or the rock fall impact may render a moving vehicle uncontrollable resulting in a fatal collision outside the limits of the roadway or with other vehicles. At the other extreme, a moving vehicle may be fully functional following a rock fall impact and the driver could maintain control of the vehicle and avoid any physical injury despite damage to the vehicle.

The size, speed, type of movement of a rock and the impact point on the vehicle will also affect its potential to harm the occupants of a vehicle. If a rock is rolling the potential for harm is less than if it is bouncing or in free fall. A rolling rock commonly has less kinetic energy than a falling rock and its trajectory is along the ground. Therefore it is less likely to effect passengers 15 cm or more above the road level in a vehicle.

Moving vehicles negotiating fallen rocks as obstacles on the road require different considerations. On most highways, fast travel is expected, therefore braking and or avoidance of rocks on the road is the greatest concern. It is demonstrated in section 5.4.1 and section 5.4.3 that in at least one case the probability of being hit by a rock is considerably less than the probability of encountering a rock on the road. The increased stopping capabilities afforded by slower travel more than offsets the advantage of decreased exposure time from falling rocks when higher speeds are employed.

For all three cases the size and robustness of the vehicle will determine how severely the vehicle and its occupants are effected. And in both the moving vehicle cases the response of the operator may effect the outcome of the interaction.

4.3.5 Fault tree and event tree analysis

Fault and event trees afford flexible representation of pertinent events that lead to an outcome. A fault tree represents in a logical manner, conditions and factors (usually faults) that can result in a specific undesirable event. The flexibility of a fault tree is useful for summarizing a series of complex events. Fault tree logic is also useful in relating the known recorded outcomes and other possible events. The fault tree in figure 4.2 illustrates the possible outcomes given an instigating event. A discussion of the right branch is contained in section 4.5.3.

An event tree considers the range of possible events that lead to specific outcomes. Russell (1976) provided an example of an event tree for a slope stability problem in a mine. Figure 4.1 is an example of an event tree analysis for a rock fall due to rainfall resulting in a probability of someone being impacted. For each event there are a set of outcomes that can have probabilities assigned to them.

Figure 4.1 indicates that if it rains every third day once in 61 days there will be a rock fall due to rainfall when nobody is impacted. Once in 6,000 days (or 16.4 years), someone will be impacted.

4.5 Risk calculation

The final step in a risk analysis is the calculation of the risk. The methodology outlined in this research only considers the hazards directly associated with a vehicle being hit by a falling rock, or hitting a fallen rock. Additional hazards resulting from a moving vehicle interacting with the elements of the road or other traffic are not considered because of the number of confounding conditions that would require integration in the analysis. As a result, only the first vehicle to encounter a fallen rock is considered. If a vehicle rock impact occurs, the assessment of the resulting risks to other highway users is beyond the scope of this research.

The calculation of rock fall hazard is a quantitative expression of the expected return period for a vehicle/rock fall accident. As described three different hazards exist, a falling rock hitting a moving vehicle (section 4.5.1), falling rock hitting a stationary vehicle (section 4.5.2), and a moving vehicle hitting a fallen rock (section 4.5.3). Each event is different and requires an independent analysis.

4.5.1 Moving vehicle / falling rock

The computation of the hazard of a vehicle being hit by a falling rock while moving is completed by considering the number, size and speed of the vehicles and the estimated number of rock falls that reach the road per year for a given length of road. Several assumptions have been made to allow an expression to be derived.

a) The vehicle speed is the posted speed limit.

b) The average length of a vehicle can be used to represent all vehicles. As a result an average hazard is computed. The hazard for an above or below average length vehicle being struck by a rock can be estimated by multiplying the P(A) or PAV and the length of the specific vehicle and dividing by the average vehicle length.

c) The temporal distribution of traffic is uniform throughout a 24 hour period.

d) The spatial distribution of vehicles is uniform below the potential rock fall zone.

e) The spatial distribution of rock falls within a cut is uniformly distributed.

f) The timing of each rock fall is assumed to be an independent event and therefore a uniform temporal rock fall distribution is assumed.

g) The traffic flow and rock fall are independent.

The probability of a vehicle being hit by a falling rock is an application of binomial trials. Each rock fall that reaches the road is considered a trial. The two possible outcomes are the rock impacts the road or the rock impacts a vehicle.

Given that a rock fall onto the highway occurs, there are two cases that must be considered. If the length of road, L_{rf}, effected by a rock fall is less than the average length of the road occupied by vehicles then the probability of a spatial impact given a rock fall occurs, P(S:H), equals the fraction of the highway occupied by a vehicle, F_v. If L_{rf} is greater than the length of road occupied by vehicles then P(S:H) is the fraction of a cut effected by the rock fall. Therefore,

$$P(S:H) = L_{rf} / L_c \qquad \text{for } L_{rf} > F_v * L_c$$

$$\text{and} \quad P(S:H) = F_v \qquad \text{for } L_{rf} < F_v * L_c$$

$$= N_v * L_v / 24000 / V_v \qquad (4.1)$$

where N_v is the number of vehicles at risk which is the traffic volume in vehicles per day, L_v is the average vehicle length in metres, and V_v is the average vehicle speed in kilometres per hour.

Morgan (1990) and Morgan et al. (1992) used the reciprocal of the return period as the probability of a hazard, P(H). This method is not applicable to multiple or frequent events where the probability of a given result is not the sum of the probabilities of each individual event. This is illustrated by the case of an object being thrown at two targets, A and B. If one object is thrown the chance of hitting target A is 0.50. If two objects are thrown independently the probability of hitting A is not 1.00 (the sum of the two trials) but rather $(1 - 0.5^2)$ or 0.75. This is an application of binomial probability.

Applying the binomial formula (Benjamin and Cornell 1970) to calculate the probability, P(S) of N_a vehicles being hit by falling rocks.

$$P(S,Na) = \frac{N_r!}{N_a!\,(N_r - N_a)!} P(S:H)^{Na} \{1 - P(S:H)\}^{(Nr - Na)} \qquad (4.2)$$

where N_a is the number of vehicles hit by falling rocks and N_r is the number of rock falls per year.

If N_a is zero, then equation 4.2 provides the probability that no vehicles are hit by a given number of rock falls. On substituting $N_a = 0$ into equation 4.2 and remembering that factorial of zero is unity by definition, equation 4.2 reduces to

$$P(S,N_a=0) \quad = \{1 - P(S:H)\}^{Nr} \qquad (4.3)$$

The probability that one or more vehicles are impacted by a rock fall, $P(S,N_a>=1)$ is one minus $P(S,N_a=0)$. For convenience P(S) will always be considered for $N_a >= 1$. Therefore the probability of at least one vehicle occupying the location of a rock fall is

$$P(S) \quad = 1 - \{1 - P(S:H)\}^{Nr} \qquad (4.4)$$

Since a moving car is always occupied by one or more occupants and F_v of a cut is occupied all the time, the temporal occupancy of a cut, P(T:S) is unity. The probability of at least one accident, P(A) is the product of P(S) and P(T:S). Therefore P(A) = P(S) in this case.

The probability of an individual being in an accident, PAV, can also be calculated. The probability of a rock hitting a single vehicle, P(S:H), is the equal to the fraction of a cut occupied by the vehicle. Therefore

$$P(S:H) \quad = F_v$$

$$= L_v / L_c \qquad (4.5)$$

P(S) is calculated using equation 4.4. The probability that the vehicle is in a cut when a rock fall occurs, P(T:S) is equal to the fraction of a year the vehicle is in a cut. Using a single pass through a cut as a standard

$$P(T:S) \quad = t / 8{,}760$$

where t is the time at risk which is the travel time through a cut in hours. The travel time,

$$t \quad = L_c / V_v / 1000$$

Therefore $$P(T:S) \quad = L_c / V_v / 8{,}760{,}000 \qquad (4.6)$$

$$PAV \quad = P(S) * P(T:S) \qquad (4.7)$$

For comparison to the Just situation the risk of a moving vehicle being hit by a falling rock is calculated in section 5.4.2 using the traffic volumes at the time of the Just incident.

4.5.2 Stationary vehicle / falling rock

The computation of the probability of being hit by a falling rock while a vehicle is stationary beneath a cut is dependent on the time the vehicle is stationary. Assumptions b, e and f from 4.5.1 and one additional assumption, h have been made to allow an expression to be derived.

h) The vehicle location and the rock fall location are independent.

As with the probability of a rock hitting a moving vehicle P(S:H) is equal to the fraction of the road occupied by vehicles, F_V.

$$P(S:H) = F_V$$

When the number of vehicles stopped in a cut, N_V is known.

$$P(S:H) = N_V * L_V / L_C \qquad (4.8)$$

where L_V is the average vehicle length (m), and L_C is the length of the cut (m). When only the spacing of the vehicles is known

$$P(S:H) = (L_V - S_V) / L_V \qquad (4.9)$$

where S_V is the spacing of the vehicles.

Again P(S) is calculated using equation 4.4. P(T:S) is the probability of temporal impact given spatial impact. This is the probability that the vehicles will occupy the section of a cut given that the rock fall occurs on a specific section. Since the vehicles are stationary P(T:S) equals the portion of a year the vehicles occupy.

$$P(T:S) = t / 8760 \qquad (4.10)$$

where t is the time at risk which is the time vehicles are stationary in a cut in hours.

Then $$P(A) = P(S) * P(T:S) \qquad (4.11)$$

The analysis for an individual being hit by a rock fall could also be computed but is not included in this research. This analysis should be completed with respect to the area occupied by an individual and the areal rock fall distribution, because of the large variation in rock fall impact with distance from the rock face.

The probability of a rock hitting an individual's vehicle in a cut is calculated by reducing the P(S:H) to that fraction of a cut occupied by a single vehicle.

$$P(S:H) = L_V / L_C \qquad (4.12)$$

Then using equation 4.4,

$$P(S) = 1 - \{1 - P(S:H)\}^{Nr} \qquad (4.4)$$

From equation 4.10

$$P(T:S) = t / 8760 \qquad (4.10)$$

then using equation 4.7

$$PAV = P(S) * P(T:S) \tag{4.7}$$

4.5.3 Moving vehicle / fallen rock

The computation of the probability of a moving vehicle hitting a fallen rock is dependent on several factors and, as a result, there are at least four sub sets of this event. First, the rock must be of a sufficient size to affect a vehicle, otherwise the driver will drive around or over the rock fall debris. Therefore, only rocks larger than some minimum will be considered. Second, the rock fall may occur outside or within the driver's decision sight distance (DSD). The DSD is used rather than the stopping distance because the decision to avoid a rock or to stop is complex because the existence of oncoming and following traffic must be considered by the driver. If the rock falls outside the DSD, the driver should be able to stop or avoid the rock on the road. If the rock falls inside the driver's DSD, the probability that the vehicle will impact the rock is increased. The faster the vehicle velocity, the greater the DSD and the higher the probability that a rock falls within the DSD. Therefore, in this case, faster travel increases risk. Third, there is also the possibility that, due to road conditions, the sight distance is less than the decision distance. In this scenario, the probability of the vehicle impacting the rock increases with the decrease of the sight distance. Fourth, if the traffic volume is high, the sight distance for a rock on the road will be reduced to the vehicle spacing. Figure 4.2 illustrates the relationship of each of these conditions. Only the condition where the rock falls within the DSD without reference to sight distance will be considered in this analysis. This can be accomplished using the same analysis as for a falling rock hitting a moving vehicle by increasing the effective size of the vehicle and requiring that the rock fall size be larger than some minimum.

The assumptions a), c), d), e), f), and g) from 4.5.2 have been made to allow an expression to be derived. Additional assumptions required are

j) If the first vehicle to encounter a fallen rock is able to avoid collision with the rock it is assumed that all subsequent vehicles will also be able to avoid the rock. As a result the analysis is independent of the time it takes for the rock to be removed from the roadway. As noted previously, only the first vehicle to encounter a fallen rock is considered in this risk analysis.

k) The rock fall events that pose hazards to vehicles include only those rocks large enough to affect the performance of a vehicle. To pose a hazard to vehicles the diameter of a rock fall must be 15 cm diameter or larger. This is the clearance of an average passenger vehicle.

l) The effective vehicle length is assumed to be half the decision sight distance for the posted speed limit. The hazard posed by a rock falling on the road increases the closer the rock falls in front of the vehicle. Assuming zero hazard for the rock falling the decision sight distance in front of the vehicle and a hazard probability of unity for the rock falling immediately in front of the vehicle, setting the effective vehicle length to half the sight distance will result in an average hazard for this condition.

The fraction of a road occupied by half the driver's decision sight distance, F_v, can be calculated. Again,

$$P(S{:}H) = F_v$$

$$= N_v * L_{dsd} / 48000 / V_v \qquad (4.13)$$

where N_v is the number of vehicles at risk which is the traffic volume in vehicles per day, L_{dsd} is the length of the decision sight distance in meters, and V_v is the average vehicle speed in kilometres per hour.

Therefore, a driver's decision sight distance occupies F_v of the road at any given time. The methodology derived in 4.5.2 can now be used with the condition that N_r include only those rocks larger than 15 cm in diameter.

As in 4.5.1, the probability of an individual being in an accident is calculated for this case. The probability of a vehicle hitting a rock, P(S:H), is the equal to half the fraction of a cut occupied by the driver's DSD. Therefore

$$P(S{:}H) = F_v$$

$$= L_{dsd} / 2 / L_c \qquad (4.14)$$

Then equation 4.4 gives the P(S). The probability that the vehicle is in the cut when a rock fall occurs, P(T:S), is equal to the fraction of a year the vehicle is in the cut. Using a single pass through a cut as a standard

$$P(T{:}S) \text{ is } = t / 8{,}760 \qquad (4.10)$$

where t is the time at risk which is the travel time through the cut in hours. The travel time,

$$t = L_{dsd} / V_v / 1000$$

Therefore $$P(T{:}S) = L_{dsd} / V_v / 8{,}760{,}000 \qquad (4.15)$$

Then using equation 4.7

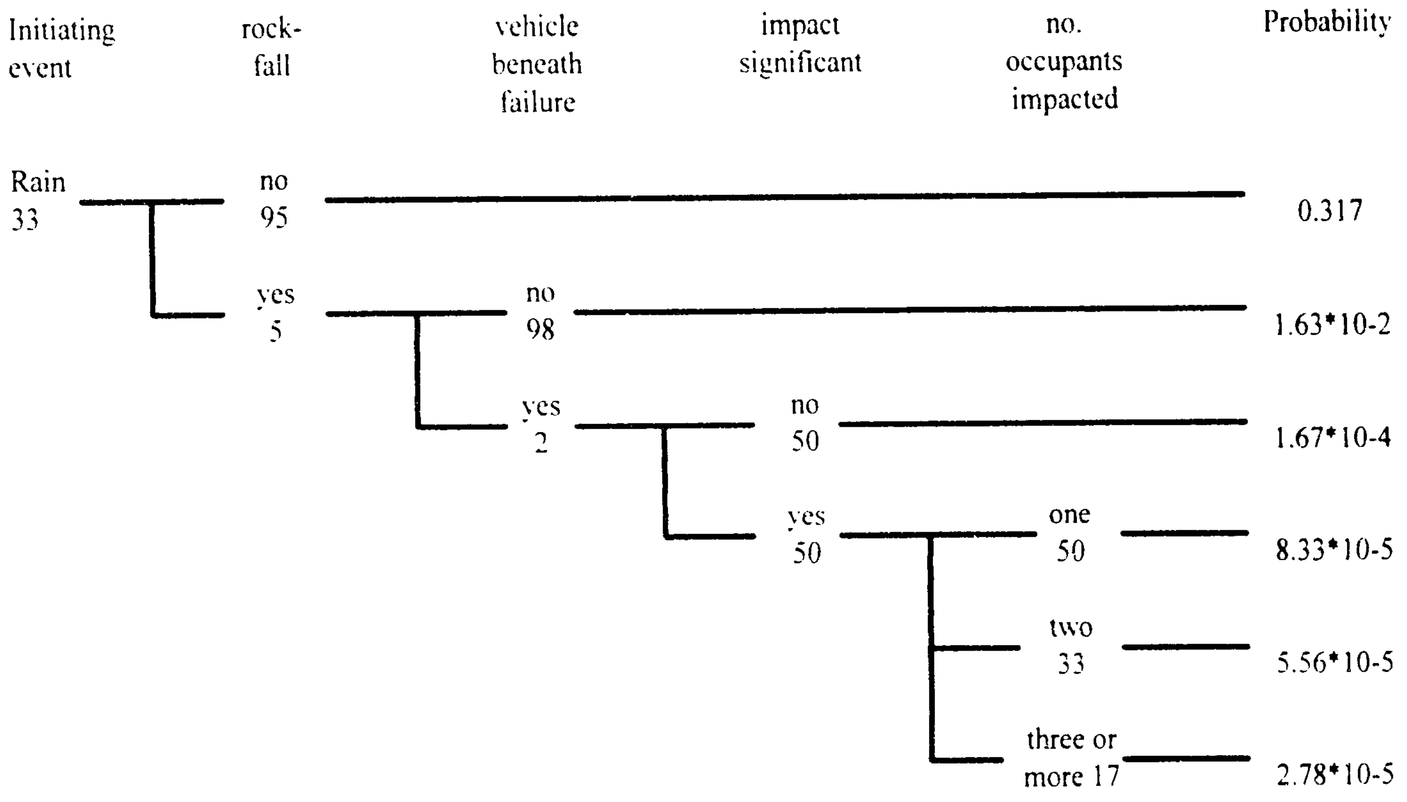
$$PAV = P(S) * P(T{:}S) \qquad (4.7)$$

4.5.4 Risk of death calculation

The probability of death as the result of a rock fall is equal to the product of the probability of one or more vehicles being hit, P(A) and the probability of loss of life of an occupant given a vehicle is hit by a rock, P(L:T). P(L:T) is a function of the size of the rock, the number of occupants in the vehicle and the location and nature of the impact. It is also a function of the capability of the vehicle to protect or expose the occupants to an impact and resulting hazards including flying glass or explosion. P(L:T) will also be different for each type of rock/vehicle interaction. Although P(L:T) has not been investigated in this study some estimates have been made in section 5.4.4 for each of the three cases to allow the calculation of the risk of death due to rock fall. The risk of death to a commuter or frequent user of the highway is the product of the probability associated with a single trip through the cut and the number of trips per year the specific user completes.

4.6 Documentation, Verification and Analysis Update

The standardized requirements for documenting, verifying and completing an analysis update are fully described for a risk analysis in the CAN/CSA (1991) publication.



(events in percent)
Probability of a traveler being impacted. P(A) = (8.33 + 5.56 + 2.78)*10-5 = 1.67*10-4

Figure 4.1 Example of an event tree for rock fall on a highway

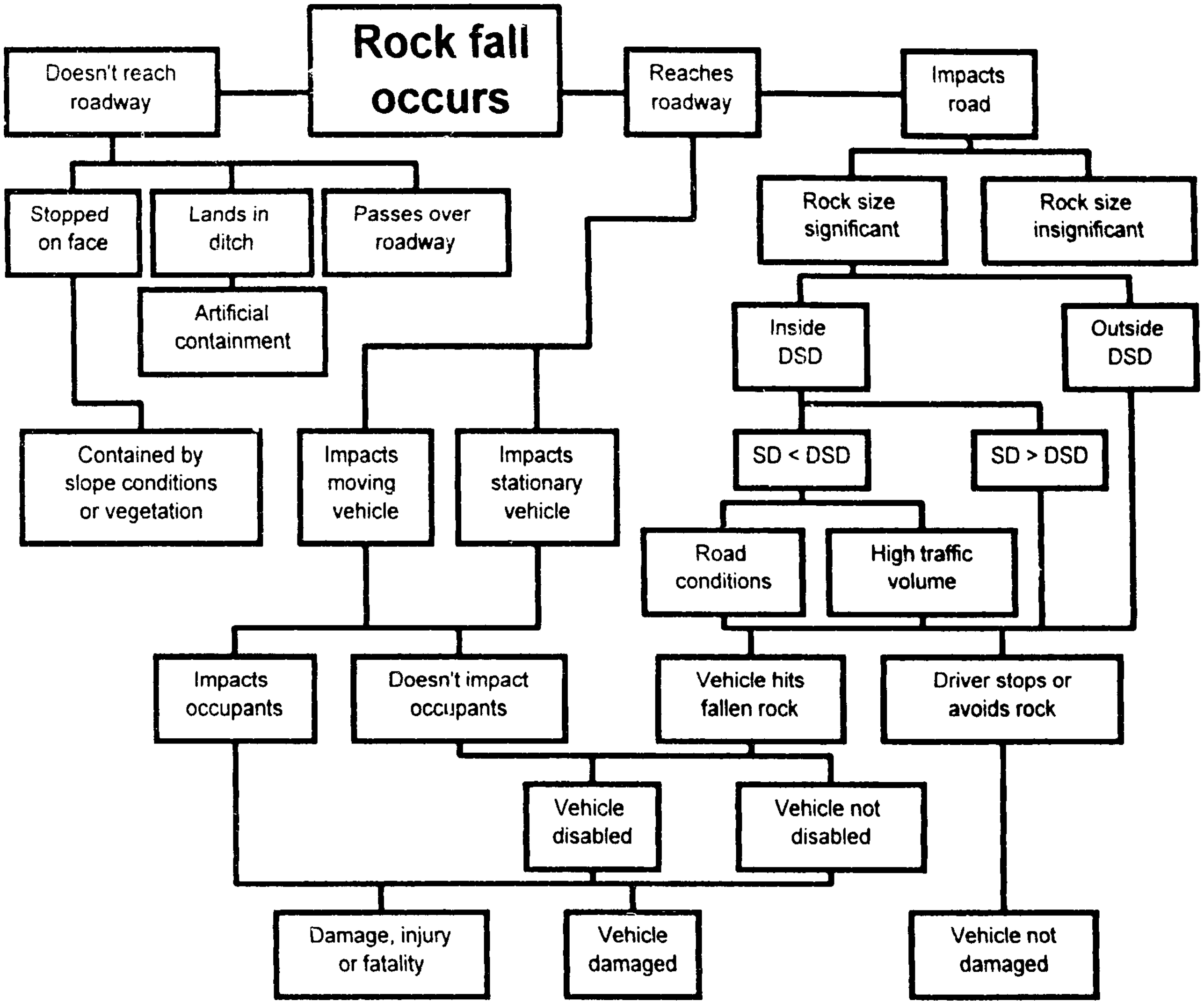


Figure 4.2 Fault tree for rock fall on a highway

5.0 Risk analysis for rock fall at the location of the Just Case on B.C. Highway 99

5.1 Introduction

This rock fall risk analysis for the Just v. the Province of British Columbia case is an example of the application of the methodology described in chapter 4. The Just case set a legal precedent (Klar 1990, Woodall 1992) when Just was awarded compensation by the B.C. Supreme court (Donald J. 1991) for losses resulting from a rock fall on January 16, 1982. Subsequently Lewis (Smith 1994) was awarded compensation when her husband was killed by a falling rock at Porteau Bluffs 3.5 km north of the location of the Just Case.

5.2 Scope definition

The objective of a risk analysis of the Just Case is to determine the level of risk from the hazard of rock fall that vehicle occupants place themselves in when using a specific section of the Highway 99 from Horseshoe Bay to Squamish. Rock fall events present several hazards. Rock falls can impact on moving vehicles directly. They can also fall on stationary vehicles delayed by highway maintenance as in the Just Case. Rock fall hazards also include the obstruction or blockage by rocks on the road prior to the approach of a vehicle.

5.3 Hazard identification

5.3.1 System

The system consists of the 480 m portion of B.C. Highway 99, the Sea to Sky Highway running below a rock slope known as the Argillite Cut. The Cut is located at 49 32' 20" latitude and 123 14' 50" longitude (figure 5.1) approximately 25 km north of Vancouver. The highway is classified as a rural arterial (Canadian Good Roads Association 1986) having a posted speed limit of 80 kmph.

The boundaries of this analysis are the Argillite Cut from 21.4 to 21.9 km north of Horseshoe Bay on Highway 99 (figure 5.1). This includes a 480 m long segment of highway below a cut slope with a maximum height of 100 m. The exposure of highway traffic to the hazard of being impacted by a rock while moving, being impacted by a rock while stopped on the highway, and driving into a rock that has already fallen on the road is considered.

The environment of the portion of Highway 99 is characterized by a specific geology, geometry, vegetation and climate each of which is subsequently described in detail.

The influences that affect the area include erosion, weathering, anthropogenic modification and biological activity. Anthropogenic effects include excavation, scaling, rock anchoring and bolting, shotcreting, and defoliation. Biological activity is predominantly disturbance by root growth.

The highway is considered under normal operating conditions. Normal conditions exclude such additional hazards as earthquakes or other large events which originate outside the system.

5.3.2 Previous investigations

5.3.2.1 Geology

The geology of the eastern shore of Howe Sound has been studied by Leroy (1908), James, (1929), Armstrong (1953, 1960), and Roddick (1965). McColl (1987) presented an overview and synthesis of the historical mapping and geologic investigation of this region. In general, the area is characterized by small pendants of Upper Jurassic - Lower Cretaceous volcanic and sedimentary rocks in igneous rock. The sedimentary and volcanic rock were classified as part of the Britannia Formation (James 1929). This sequence was deposited penecontemporaneously with the plutonic activity that formed the underlying igneous rock (Armstrong 1960). The Argillite Cut exposed part of a pendant identified as the Gambier Group (Armstrong 1953). Roddick (1965) subdivided the Gambier Group into three units and classified the Argillite Cut as part of the middle unit and the Britannia Formation as the upper unit.

Armstrong (1960, p. 18) described the sedimentary and volcanic rocks of Howe Sound as being

> "... generally separated into those exhibiting weak or no metamorphism, and those exhibiting medium grade metamorphism. The former including sedimentary and volcanic rocks. The sedimentary rocks in order of abundance are thinly bedded slaty argillite, argillite, siltstone, greywacke, tuffaceous greywacke, limy argillite, limestone, and conglomerate; and the volcanic rocks are principally pyroclastics, and to a lesser extent, flows of mainly andesitic composition but including dacite, trachyte and basalt. Some areas contain all the above types."

Armstrong (1960) specifically described the area surrounding the Argillite Cut using the highway mileage from Horseshoe Bay as a reference. Due to changes of the highway alignment in the past 33 years the distance to the Argillite Cut has changed to 21.4 - 21.9 km from the Horseshoe Bay intersection. This correlates with the 12.1 to 12.3 miles in the Armstrong's field guide (1960 p. 22).

> "12.1 to 13.8 About mile 12.1 the volcanics are in contact with argillites and cherty argillites which outcrop from here to about mile 12.6. At the contact they strike N 35 E. and dip steeply but the dip changes to nearly horizontal from mile

> 12.3 north. From mile 12.6 to mile 13.8 (Porteau) thinly bedded slaty argillite, siltstone and greywacke outcrop, a facies similar to that exposed at STOP 9. From mile 12.6 to mile 13.0 the attitude of these sediments is nearly horizontal and from about mile 13.0 to mile 13.8 they trend N.W. and dip N.E. They are intersected by masses of quartz porphyry with granophyric texture, most of which are bounded by faults. Because of well developed bedding, numerous faults, and steep slopes, the sediments from mile 12. to mile 13. contribute to numerous landslides. At Porteau the sediments contain several granitic sills and to the north they are in contact with a younger granodiorite. A foot-wide zone of cordierite hornfels has been developed at the contact."

Roddick (1965, p. 50) described several other characteristics of the geology of the Argillite Cut and its surroundings. The argillite within this middle unit is exposed in up to 305 m thick sequences

> "... of argillite and slate with interbeds of quartzite. The uppermost part contains argillite and quartzite in the approximate ratio of 5 to 1.
>
> Most of the argillite or slate is very fine grained, black, and carbonaceous. The fissility of the rock varies from negligible to extensive enough to produce sheared 'paper' slates. Some of the argillite is grey and siliceous or cherty; some is greenish and probably tuffaceous."

The structure of the middle unit is characteristically complex and is not well understood. According to Roddick (1965, p. 52-53) "Along the highway to Squamish the rocks are cut by innumerable faults and open and tight folds are exposed." The bedding strikes generally north-south but the dips vary. One fossil locality is identified within the Britannia Group (Roddick et al. 1979) north of the Argillite Cut on Bertram Creek. This Albian ammonite defines a Lower Cretaceous age for the rock in the Argillite Cut.

Kosar (1979) and Stewart (1987) completed investigations of the Porteau Bluffs and identified the major set of through going joints as originating from stress-relief, exfoliation processes. This major set is oriented roughly parallel to the highway dipping 50 degrees out of the face. They also identified a secondary joint set striking east/west and near vertical.

5.3.2.2 Rock fall hazard

The rock fall hazard of the B.C. Highway 99 has been commented on by several groups.

Nasmith (1976) included some comments about the rock fall history and the geotechnical remediation works of the Argillite Cut.

The Ministry of Transportation and Highways (MOTH), Geotechnical and Material Engineering Branch subdivided the Argillite Cut into five zones and identified the potential for raveling and planar and slab failures (MOTH 1982). The Cut was described as being through argillite with height of 50 m high and length of 400 m. The northernmost zone was identified as having vertical jointing. Check scaling was recommended requiring 10 man-days of scaling, and 550 m^3 of trim blasting was suggested at that time.

The B.C. Supreme Court decision indicated (Donald J. 1991) that "The maintenance section of the Department of Highways requested scaling for the Cut in 1979 and 1980." and "Apparently, the requests for scaling made in 1979 and 1980 were not fulfilled."

Eisbacher (1983, p. 20) identified the 5 km of the highway between Brunswick Point and Porteau Cove including the Argillite Cut, as "one of the most serious rockfall zones in southwestern British Columbia". He described the bedrock as "intensely fractured northwest-trending meta-argillite and volcani-clastics in the Brunswick Point area,...".

Kosar (1979) researched the effective friction angle of the rock at the Porteau Bluffs 3.5 km north of the Argillite Cut on B.C. Highway 99. Stewart (1987) considered the geotechnical design of the area and proposed a tunnel to avoid the Porteau Bluffs.

MOTH (1988) described the Argillite Cut for their stabilization summary.

> "Cut length of 400 m with a cut height of up to 100 m. Cut contains shotcrete at lower elevations. Rock type is Argillite at lower elevations overlain by volcanic tuff. Argillite is weathered and altered whereas tuff is massive and moderately hard. Jointing is vertical. Failure modes are raveling and toppling. "

They recommended 120 man-hours of scaling and 80 m of bolting be installed at an estimated cost of $12,000.

Hungr and Evans (1988, 1989) reviewed the Just incident in the Argillite Cut. They inspected the slope and identified the rock fall source, intermediate impact location, and trajectory. Their computer rock fall modeling indicated that prior to hitting Just's vehicle the rock fall's last contact was above the Cut rock slope following which it descended almost vertically to the road level with an impact velocity of 28 m/s (100 km/hr). This is classified as extremely rapid (Cruden and Varnes 1994) and is consistent with the velocity range defined for rock falls.

A description of the Argillite Cut and the rock fall incident specific to the litigation was also given in each of the decisions of the Just versus the B.C. Government court actions (McLachlin J. 1985, Taggart J. et al. 1986, Cory J. and Sopinka J. 1989, and Donald J. 1991). Justice Donald (1991) included details of the mechanism and nature of the rock fall that killed Just's daughter.

5.3.3 Field Research

The field research consisted of three phases: geotechnical mapping, and two surveys of the rock fall impact marks separated by five months. During the geotechnical mapping I applied the Rockfall Hazard Rating System (Pierson et al. 1990) and characterized the Argillite Cut to determine the potential for rock fall and the expected size of rock fall events. The two impact mark surveys quantified the number, size, and location of the impact marks in the highway asphalt and identified which were made by rock falls and which were not.

5.3.3.1 Geotechnical mapping

On July 20, 21 and 23, 1993 I mapped the Argillite Cut. This included inspection of the toe of the slope exposed along the highway, the perimeter of the upper portion of the face and a discontinuous traverse of the face approximately 50 m above the roadway. The mapping confirmed much of the information noted by previous investigators. A summary of the results of the mapping are presented in exploded section in figures 5.2, and 5.3.

The geomorphologic setting of the Argillite Cut is within a glacial fjord with characteristic steep valley walls. The area was last glaciated 10,000 years B.P. (Clague 1981). The highway through the Argillite Cut is approximately 100 m above mean sea level (msl) with the British Columbia Rail (BC Rail) line running below it about 30 m above msl. As can be seen from the oblique aerial photo collages (figure 5.4 and 5.5), the Argillite Cut intersects the slope of an isolated hill separated from the main fjord wall. The geomorphologic features of the area are also illustrated on the 1:50,000 NTS map 92 G/11 of the Squamish area (Department of Energy Mines and Resources, 1981) and Burnett Resources Surveys Limited (1982) aerial photographs. According to MOTH landmark signs the Cut is bounded to the north by Kallahne Creek and to the south by Bertram Creek. The 1:50,000 NTS map indicates that both Bertram and Kallahne Creek are north of the Argillite Cut.

The Argillite Cut has a total height of less than 130 m above the highway with an overall slope of 67 degrees. At present the slope is bare rock with some vegetation and thin colluvium. The trees and shrubs were removed in 1987 prior to scaling (see Table 5.2) but, since then, small deciduous trees and some shrubs have re-established themselves. The tuff and argillite can be distinguished by their colour and weathering characteristics. The competent tuff is lighter and forms rounded benches with visible glacial striations separated by near-vertical, joint-controlled faces (figure 5.4). The argillite forms flatter slopes, most of which have been treated with shotcrete to reduce weathering. Where it is exposed, the argillite is darker than the tuff and is more vegetated.

Access to the face was obtained via the southern end. Additional access is available from the power line access to the east of the Cut (see figure 5.5) and the branching trails off the Deeks Lake trail that starts from the highway north of the Argillite Cut at km 22.3.

The geometry of the Argillite Cut is complex. For discussion purposes I have divided the 480 m length of the Cut into three units: the south face, central face, and the north face. The south and central faces consist of a 10 - 15 m, 55 - 75 degree excavated face with a 30 - 40 degree natural bench under a 0 - 90 m natural 60 - 90 degree stepped rock face. Figure 5.6 shows three typical cross sections of south, central and north faces. The argillite has been extensively treated with shotcrete which supports the excavated face angle at 55 - 65 degrees and near vertical immediately below its upper contact. The stronger tuff has an overall slope angle of 70 - 80 degrees; it is vertical and overhanging on parts of the face. The north face consists of a 70 m face of tuff as shown in figure 5.5.

The Argillite Cut exposes two lithologic units. The two units are interbedded but their structural relationship is partially obscured by metamorphism and possible faulting (Armstrong 1960). The cut consists of a 10 - 15 m face of northeast dipping argillite along the southern portion of the exposure overlain by up to 90 m of competent layered tuff. In addition, there is a 75 m long exposure of tuff interbedded within the argillite at the road level, although much of the tuff/argillite contact is obscured by shotcrete. No evidence of faulting was found but the metamorphic conditions indicated by the lithologies may have masked any shear zones. The northern portion of the Cut consists of tuff flows from road level to beyond the crest.

The argillite varies in appearance, jointing and exposure. In some areas it is lacking in any cleavage but in other areas it has a well-developed, slaty cleavage (Roddick 1965). The overall variability in cleavage development appears to be the result of metamorphism rather than stratigraphy. The variation in cleavage spacing and continuity influences the appearance, competency and performance of the argillite in the Cut. The cleavage predominantly dips steeply east as illustrated in the stereonet of the discontinuities in the argillite (figure 5.7).

The tuff is competent with several continuous, parallel joints. Bedding, S1 within the tuff is indicated by several 0.2 - 0.5 m thick, 5 - 15 m spaced undercut zones of erodible, broken tuff along sub-horizontal to moderately dipping discontinuities. The 10 - 15 cm open, joint dipping from left to right in the lower left portion of figure 5.9 illustrates one of these surfaces. These bedding planes may have a higher permeability producing springs where they daylight. The resulting water flow erosion would explain the undercutting. A similar effect was identified in a basalt sequence in St Helena by Culshaw and Bell (1991).

There are two dominant sets of joints in the tuff (figure 5.8), one sub vertical and parallel to the highway, S2 and the other sub vertical and generally orthogonal to the traffic flow direction, S3. The parallel joint, S2 has a regular spacing of 2 - 3 metres. This joint set has a horizontally continuous trace up to 10 m long. The joint set's vertical trace appears to be up to 10 m based on the faces exposed in the Cut.

The orthogonal joint set, S3 occurs in joint swarms spaced up to 10 m. In other locations this joint set has healed or it is discontinuous. The joint swarms have allowed differential erosion producing a set of prominent gaps in the face. These gaps give the Argillite Cut its characteristic blocky appearance and form the small gully between the southern and central portion of the Cut (figure 5.5)

In addition to the two dominant joint sets in the tuff, there is also a discontinuous sub horizontal jointing, S4; and exfoliation jointing, S5 (figure 5.8). The exfoliation jointing, S5 is poorly developed, shallow and has limited continuity. Along with glaciation, the exfoliation jointing and post glaciation erosion has produced the convex shape of the crests of the rock face steps (figure 5.4). In some areas the exfoliation jointing intersects the face (figure 5.11).

The contact of the argillite and the tuff is parallel to the jointing in the argillite, dipping steeply to the east. The contact is typified by closely spaced jointing in the tuff suggesting a cooling or contact aureole on the tuff's basal surface (figure 5.10). Alternately the jointing could be the result of stress concentrations in the stiffer tuff during tectonic flexure causing fracturing.

5.3.3.2 Rockfall Hazard Rating System

Prior to the Just incident, the B.C. MOTH was specifying locations for rock scaling when resources and manpower were available. Subsequently MOTH developed a comparative method of ranking areas by hazard. They then employed their limited resources to reduce the risks posed by the areas presenting the greatest hazard. Since 1993 the B.C. MOTH has adopted the FHWA Rock fall Hazard Rating System (Pierson et al. 1990) to reduce the subjective aspects of their rating.

The rock fall hazard of the Argillite Cut was assessed using the Rockfall Hazard Rating System (RHRS) (Pierson et al. 1990). Although the RHRS contains five parts only the second and third stages, the preliminary rating and detailed rating of slopes respectively, are applied in this research. The slope inventory stage was omitted due to the limits of the research and the prior identification of the Argillite Cut as the site of interest following the Just v. British Columbia court cases. The fourth and fifth stages were omitted because they are outside the scope of this research.

To illustrate the variation in the Argillite Cut the face was divided in six zones of various lengths each having different RHRS ratings (figure 5.2 and 5.3). The results are compiled in Table 5.1. Section A has had relatively little rock fall activity and therefore has a comparatively moderate rating. Section B contains more areas of fractured rock and therefore received a higher score for geological structure but because it is predominantly tuff rather than argillite the friction score is reduced. Section C is the lowest face and has a lower block size being predominantly argillite, giving it the lowest total score. Section D has the highest concentration of jointing and is more significantly effected by surface water flow yet it has a short face length resulting in a moderately high rating. The slope height of section E is considerably higher than the other sections but this does not affect its score because of the upper limit of 100 on each of the category scores. Extensive scaling and rock bolting have minimized rock fall activity resulting in a moderate score for this section. The most northerly section, F is the longest and the most active and therefore receives the highest section score. The RHRS score for the entire Cut is higher than any single portion due primarily to the high length-score of the Cut and the contribution of each of the sections.

5.3.3.3 Rock fall-impact asphalt-damage mapping

In addition to the geotechnical mapping of the Argillite Cut, damage to the asphalt pavement below the Cut was mapped to identify the number, size, and distribution of the depressions caused by rock fall impacts. These depressions are isolated, sharply-defined, circular to sub-angular, and concave. The depressions often included one or more angular, tapered intrusions into the asphalt but can also be irregular spherical depressions (figure 5.12 and 5.13). Rock fall impacts can be distinguished from other damage based on these characteristics.

Flaws in the pavement surface in the Argillite Cut differ from impact marks in several ways. They generally have near vertical sides and irregular sometimes sinuous outlines. Some appear to be imprints of organic material or other detritus embedded into the pavement during rolling which has subsequently decayed, eroded or been displaced by tire wear. Other non rock fall impact marks were identified. These marks are orientated parallel with the traffic flow and are shallow and elongate in shape. They are probably formed when objects fall or drag from a vehicle. An example of one of these marks is shown in figure 5.14. The youth (4.75 years minimum) of the pavement below the majority of the Argillite Cut makes the identification of rock fall impacts more reliable since less non rock fall damage has occurred and there is little weathering of the marks.

As discussed in section 4.3.3.1. in addition to impact marks, mechanical damage caused by the equipment used for the removal of fallen rock is present in areas of extensive rock fall. Figure 5.15 illustrates mechanical damage in conjunction with rock fall impact marks in the pre March, 1989 pavement at the north end of the Cut.

There are several limitations to the rock fall impact information. First, the magnitude of rock fall impact damage depends on the properties of the asphalt, the shape and size of the rock and the trajectory of the rock. Several properties of the asphalt affect the damage resulting from a given rock fall. These include the age of the asphalt, its temperature at the time of impact, the asphalt viscosity and density, and the aggregate percentage, size and proportion. Among these factors, the age and the temperature of the asphalt vary over time. As a result, a given rock fall could produce a different sized impact at different temperatures and at different times in the asphalt's life. In addition, the location of a rock fall with respect to aggregate particles will effect the magnitude of a rock fall impact. The size of the impact is reduced as the energy of the rock fall decreases or the size of the asphalt aggregate increases.

Second, the velocity of a rock fall particle cannot be determined unless the source of the rock fall is known but a multitude of possible sources exist above any given impact damage location. Assuming that the temporal and spatial variations in the rock fall-impact/asphalt-damage relationship are limited, the volume of each impact is proportional to the impact energy.

Third, there is a minimum size of impact mark that is distinguishable from the natural surface roughness of the pavement. The size of smallest identifiable mark is about 3 cm diameter or the maximum aggregate size although during mapping smaller marks were identified and recorded. During the mapping of the Argillite Cut a 3 cm diameter fragment of tuff fell from the face from a height of 20 metres but caused no visible damage to the asphalt. The fragment remained on the road until tire action gradually moved it to the side of the pavement.

Fourth, several impacts in the pavement could have resulted from the same rock fall event. Using the impact marks to identify rock fall events will result in an overestimate of the rock fall frequency if several of the impacts were caused by the same event. Conversely, assuming that closely spaced rock fall impact marks are the result of a single event rather than multiple events, from a prolific rock fall source, may underestimate the rock fall frequency. Assuming each impact mark represents a rock fall event allows an estimate of an upper bound on rock fall frequency. Judgment as to the number of simultaneous rock fall impacts can be used to obtain a best estimate of the rock fall frequency.

Mapping of the rock fall impacts included quantifying each mark's location from the south end of the Cut and its distance from the north bound fog line. In addition, the depth and the dimensions parallel and perpendicular to the centreline of the road were measured for each mark. The area of each mark is the product of the two horizontal dimensions. Assuming the shape of each mark approximates an inverted pyramid the volume of each mark is one third its depth times its area. The mapping results are tabulated in appendix A. Figure 5.16 illustrates the frequency distribution of the volume of rock fall impacts and modeled exponential distribution. The cell size used for this analysis is based on the sample size following the recommendations of Benjamin and Cornell (1970, p. 8). Using the analysis of Benjamin and Cornell (1970, p 374-375) for the exponential frequency distribution, lambda = 78.16 cm^3. An exponential distribution was chosen because of its ease of use and the similarity of the function to published rock fall size distribution data from other areas (Gardner 1970 and 1977, Douglas 1980, and Whalley 1984). The size and distribution of rock fall impact marks through the north and south halves of the Argillite Cut are shown in figures 5.17 and 5.18 respectively. The scale perpendicular to the direction of traffic is 5 times the scale parallel to the direction of traffic to illustrate the position and relative size of the marks.

It is evident in figure 5.17 and 5.18 that the greatest number of rock fall marks are close to the base of the Cut. The distribution of impact marks with respect to the east fog line is shown in figure 5.19. This demonstrates that the distance the road is from the toe of the face can significantly affect the number of rocks that reach the road. Most of the Cut has less than half a metre of asphalt outside the fog line as a result there is only one impact mark at -0.5 m. Figure 5.19 confirms Ritchie's (1963) findings regarding the importance of ditch width.

The size of the rock involved in a rock fall will have a significant effect on hazard of the event. The rock particle size depends on the discontinuity spacing of the rock mass and its weathering characteristics. It is not possible to determine the rock fall size due to the wide variation in joint spacing in the Argillite Cut. As noted the size of the rock cannot be determined from the impact mark due to the existence of several confounding variables.

Several assumptions must be made to derive any rock fall block size information from the impact marks. Assuming that a rock fall particle can be represented by any symmetric body such as a sphere, cube or double ended pyramid the minimum volume of the rock would be twice the volume of the impact mark. Due to the penetration resistance of asphalt I have assumed that the volume of a rock is ten times the volume of the impact. This estimate of the rock fall volume is required to determine the number of fallen rocks that could pose a hazard to moving vehicles.

The rock fall impact mapping can be used to estimate the number of rock fall events that could cause harm to highway drivers. The kinetic energy of a rock impacting a moving vehicle is up to 1.4 times that of the rock hitting the road due to the velocity of the vehicle. In the Just Case Hungr and Evans (1989) predicted an impact velocity of 101 km/hr for the rock that fell on Just's car. Assuming a vehicle speed of 80 km/hr the impact velocity of the rock with a vehicle would be 28% greater than with the asphalt or a stationary vehicle. In the subsequent risk analysis I have assumed that any rock fall particle with sufficient kinetic energy to damage the pavement would damage the windshield of an automobile sufficiently to disable the driver who could lose control of the automobile or be killed.

In conclusion, 84 rock fall impacts were observed in the 393 metres length of 4.75 year old asphalt. Of these 24 were outside the fog line and therefore not on the running surface of the road. Several rock falls probably included several rock fragments each producing multiple marks for a single event. Based on field observations and mark groupings shown in figure 5.17 and 5.18 I estimate that five events producing 4 - 8 marks each occurred. This further reduces the number of rock fall incidents that are a hazard to motorists to 35. To estimate the number of rock falls within Argillite Cut I divided the number of rock falls marks in the new pavement by the fraction of the 476 metre length of the Argillite Cut covered by the new pavement. This results in an upper bound estimate of 73 and a best estimate of 43 rock falls that could impact vehicles.

Rocks impacting outside the fog line may come to rest within the fog line. Therefore they are a hazard to vehicles hitting them but would provide a reduced hazard to hitting a vehicle. In addition a rock on the road must be larger than the clearance of a vehicle to pose any hazard to the vehicle. The minimum clearance for a small vehicle is 15 cm therefore the volume of the smallest spherical rock that it could clear would be 1800 cm^3. Using the volume frequency distribution derived from figure 5.16 and the assumption that the rock volume is 10 times the impact mark volume the expected number of rocks greater than 180 cm^3 is

$$
\begin{aligned}
E(180/80) &= e^{(-0.977 * 180 / 80)} \\
&= 11.1 \text{ \% of 84 rock falls or} \\
&= 9.3 \text{ rock falls in 4.75 years}
\end{aligned}
$$

This agrees closely with the 8 impact marks larger than 180 cm^3 observed in the Argillite Cut in 4.75 years. Correcting these two values for the length of the Cut compared to the new pavement results in 2.0 - 2.4 rock falls per year.

5.3.4 Documented rock fall history

The rock fall history of the Argillite Cut on B.C. Highway 99, km 21.4 to 21.9 north of Horseshoe Bay has been compiled from several sources. The records extend from the start of construction of the Alberta Bay to Porteau section in 1955 to December 31, 1992. The records are based on MOTH records and those of their maintenance contractor.

All the sources of rock fall records have limitations. Prior to November 1988, rock fall incidents were recorded during inspections by MOTH Geotechnical and Material Engineering staff. These inspections were instigated following reports of significant rock falls by MOTH maintenance personnel. As a result, records prior to November 1988 included only those events that were of consequential magnitude or impact. Capilano Highway Services Limited (CHSL) assumed the maintenance contract for the Sea to Sky Highway late in 1988 and began systematically recording rock fall incidents after November 19, 1988 (Bartle 1993, personal communication). As with MOTH, CHSL recording of rock falls has limitations. It was revealed in the Lewis (Guardian ad litem of) v. British Columbia (Smith 1994) court case that only rocks larger than approximately 1,800 cm^3 (108 cubic inches) are recorded by CHSL personnel (Bartle 1993, personal communication). In addition, there are undoubtedly occasions when private citizen, police and CHSL employees remove rock fall debris from the roadway both larger and smaller than the 1800 cm^3 size previously noted without any record being made.

In his correspondence to MOTH Fieber (1990, p. 3) describes the data compiled and the information sources.

> The above information on past failures was gathered from personal diary entries and from Howe Sound Highway District incident reports as supplied by Capilano Highways Services Ltd. The latter source includes all incidents labeled as "slides", "rockfall" or "rock on road", where such incidents resulted in at least one lane blocked. Estimate of volume from these incidents are approximate, as very little quantitative information is available from District files.

One year following the completion of the Horseshoe Bay to Squamish section of route 99, the Regional Highway Engineer based in North Vancouver, D.D. Godfrey stated "Rockslides on the Seaview Highway north of Horseshoe Bay required continual attention. However, the new rock slopes on this highway should become stable soon"

(British Columbia Ministry of Highways 1960, p. 68). Godfrey's assessment has not stood the test of time.

As noted in section 5.3.3.1, MOTH and the 1:50,000 scale NTS map identify Bertram and Kallahne creeks differently. Although some reports use the creek signs as reference points, it is assumed that the signs have not changed and therefore the reports are consistent.

Due to independent reporting by CHSL and MOTH, two of the occurrences listed in Table 5.2 may appear twice though it is not possible to confirm this due to incomplete reporting.

During the 4.12 years between November 18, 1988 and December 31, 1992 for which CHSL systematically recorded rock falls, MOTH has identified 11 instances where a rock was found on the road. A review of the CHSL reports indicates that of these 11 events, the reports for 4 of the events suggest they may have occurred outside the Argillite Cut. In addition to those reported by CHSL, two cases were independently recorded by MOTH. Therefore the minimum number of independent rock fall events recorded in a period of 4.12 years is nine or 2.1 per year. This is within the 2.0 - 2.4 rock falls per year larger than 1800 cm^3 estimated in 5.3.3.3. The difference in recorded rock fall frequency and the impact frequency may be the result of different sampling periods and the reality that recorded rock falls may not all cause impact marks.

The variation of rock fall volume with time is shown in figure 5.20. The significant reduction in the size over the history of the Cut is possibly the result of effective remedial action and perhaps the increasing stability with time expected by Godfrey (British Columbia Ministry of Highways 1960). If the construction of the Cut is considered as a period of remedial work the data indicates three cycles of remediation followed by periods of low rock fall activity. The increase in rock fall frequency in the last 4 years is undoubtedly the result of higher usage of the road, diligent reporting and improved record keeping. Figure 5.21 demonstrates the increased reporting following the initiation of a systematic record keeping system in November of 1988. The climatic conditions prior to and during each event are reviewed in section 5.3.6.

The diurnal distribution of recorded rock fall activity (figure 5.22) indicates that most falls occur in the early hours of the day. This differs from Gardner's (1970) findings which indicated a peak in activity around noon in high mountainous terrain. Three factors may produce this difference. First, the diurnal temperature cycles of the Argillite Cut and Gardner's research area differ. Second, Gardner's recording system was designed to note rock fall throughout a 24 hour period. No systematic recording procedure exists for the Argillite Cut. Third, Gardner based his conclusions on 563 recorded rock falls.

There are 9 recorded rock falls at the Argillite Cut with information on the time of the event. As a result the statistical reliability of the Argillite Cut data is low in comparison to Gardner's.

A review of the accident records compiled between January 1, 1986 and June 30, 1991 (MOTH 1992) revealed that no accidents were recorded in the Argillite Cut during this time. To be included in the provincial accident records the event must result in significant loss. The minor vehicle damage reported on April 11, 1991 by CHSL (table 5.2) is not in the provincial accident records (MOTH 1992).

Further sources of rock fall incident documentation not pursued include the RCMP in Squamish, the West Vancouver Police, and the Insurance Corporation of British Columbia.

5.3.5 Rock fall causes and sources

The Argillite Cut is considered stable (Bartle 1993, personal communication) in comparison to the two major cuts to the north and south of it, the Porteau and Windy Point cuts respectively. The isolated nature of the hill through which the Argillite Cut passes reduces the rock fall source area. This is an important distinction from the cuts between Sunset Beach and Lone Tree Creek south of the Argillite Cut on B.C. Highway 99 that are typified by rock cuts at the base of 1000 - 1500 m mountain slopes. The total height and, therefore, the rock fall source area of the Argillite Cut slope is less than 130 m. The excavation of the Argillite Cut has not been researched but one aspect of the blasting can be interpreted from the Cut. The lack of evidence of preshear holes suggests that production blasting techniques, causing significant overbreak, were employed. It is not expected that the argillite would preserve any evidence of preshear blasting due to its fissility. However the tuff exposed along the northern 50 m of the cut contains no preshear holes either.

Three types of rock fall can be identified in the Argillite Cut. Toppling on near vertical joints (figure 5.7 and 5.8) both within the argillite and the tuff can form unstable blocks. Small falls from closely jointed zones predominantly in the tuff have resulted in recent rock falls. Similar to that noted by Culshaw and Bell (1991), toppling of vertically jointed blocks of tuff above bedding surfaces is present . Sliding of blocks on tuff bedding, S1 (figure 5.8) is also kinematically possible.

The argillite-tuff contact appears to have been the source of many of the initial rock falls in the Cut. The contrasting stiffness, jointing and durability of the two rock types probably resulted in toppling within the argillite at the contact. The evidence for this conclusion is the presence of the overhang 30 m above the road at the contact as illustrated in the section X -L2 of figure 5.6 and the number of large to intermediate size failures during the early history of the Cut (table 5.2)

Several failure triggers could occur at the Argillite Cut. Stewart (1987) noted that frequent high winds apply forces to the trees, creating moments that are opposed by the roots. Roots which penetrate fractures in the rock transfer these forces to the adjacent rock which could cause rock falls. Oliver (in Donald J. 1991) cited this as the cause of the fatal rock fall on January 16, 1982. Other mechanisms include the ratcheting effect of soil and rocks in joints noted by Cruden et. al. (1993) and Bjerrum and Jorstad (1968), freeze-thaw action, increased pore pressure along joints, and erosion of fines along a failure surface (MOTH 1992). Stewart (1987) cited Brawner and Wyllie (1976) and Brawner (1978) on the effect of vibrations in the rock caused by railway traffic and estimated that the friction angle for loose blocks could be reduced by up to 5 degrees over time. Vegetation may also increase infiltration by holding moisture on the slope and providing a conduit to open joints. Other actions that may precipitate rock falls are physical and chemical weathering, wetting and drying, snow loading and animal activity such as small rodents and nesting birds. Loosening due to vegetation (Brawner and Wyllie 1976) and ratcheting are responsible for accelerating the rock fall source development and rainfall and freeze thaw effects are the common triggers.

5.3.6 Climate

The climate is temperate coastal rain forest characterized by high rates and frequency of precipitation, low potential for freeze-thaw conditions, and frequent wetting and drying conditions.

Since the construction of B.C. Highway 99 in 1957, climatic information has been recorded at several points near the Argillite Cut. These are Lions Bay, 9.0 km to the south; Britannia Beach, 9.2 km north northeast; Squamish FMC and Squamish, 16.0 km north northeast; Squamish A (upper), 22.6 km to the north northeast; and Pam Rock, in Howe Sound 7.5 km south southwest. Of these, the climate at Lions Bay and Britannia Beach is most analogous to that of the Argillite Cut (see figure 5.1) having the same exposure and similar surrounding topography. Lions Bay initiated its atmospheric observations in July 1983 and Britannia terminated its records in October 1974. As a result Squamish, Squamish FMC and Squamish A meteorologic information is used to cover the interval between the two. The precipitation and temperature at each of these stations is similar as demonstrated by figure 5.23.

The greatest rainfall on any one observation day are listed in Table 5.3 from Environment Canada (1985).

None of these events correlate with any historically documented rock fall events on the Argillite Cut. This may indicate that extreme rainfall events alone do not cause rock falls at the Argillite Cut.

Information from the Environment Canada, Atmospheric Environmental Services (1983 - 1991) for Lions Bay is displayed in figure 5.24. Records indicate that there are 174 days with precipitation (Environment Canada 1984, Vol. 3) and 44 day of sub zero temperatures per year (Environment Canada 1984, Vol. 2) at Britannia Beach.

Stewart (1987) summarized the climatic conditions at nearby Porteau as 200 cm precipitation per year with a temperature range of -8 to 25 degrees C and estimated 20 - 25 freeze thaw cycles per year.

Unlike the debris flow hazard present along the east shore of Howe Sound (Jackson et. al. 1985) the recorded rock fall incidents at the Argillite Cut do not appear to be dependent on antecedent precipitation to saturate the slope.

The number of documented falls per month and the monthly meteorologic data from Lions Bay (Environment Canada 1983 -1991) is shown in figure 5.24. The rock fall activity is concentrated in January, March and September. January has the lowest average minimum temperature and therefore has the greatest number of freeze thaw cycles with the most depth penetration. I have not been able to explain the large number of events recorded in March. It is possible that this is the first month of the growing season in this area and new root growth and significant rainfall may instigate failures. September is the first month following the growing season with significant rainfall and this may be responsible for the increased reports of rock falls.

Detailed correlation of the climatic conditions of each of the rock falls has been completed where the data is available and is summarized in Appendix B. The 6000 m^3 event in 1969, followed the first month with negative average temperatures since the construction of the Cut. This correlation suggests frost heaving as the major cause of the rock fall. The January 1971 event occurred during the month with the heaviest rainfall since the 1969 freeze. No correlation with temperature or rainfall exists for the August 1971 event.

For the more recent events daily climatological data is available. It is documented that the January 16, 1982 rock fall that killed Just's Daughter was triggered by snow and wind (Donald 1991). The record of the rock fall in January 1984, and two falls in September 1985 do not specify which day they occurred and therefore cannot be correlated to any climatological events. The January 29, 1989 event may have occurred as a result of the first significant rain following sub zero minimum temperatures a week earlier. The March 21, 1989 and May 4, 1989 rock falls do not correlate with any temperature or rain fall events. No date is available for the September, 1990 event but the single significant rain fall on the 16th may have triggered an event. The December 18, 1990 event occurred at the onset of the first significant period of sub zero temperatures. In addition there was some rainfall prior to the freezing temperatures. Neither the March 28, 1991 nor the April, 1991 events relate to an identifiable climatologic event. In summary, five of the ten events reviewed could be related to climatologic effects.

5.3.7 Temporal exposure

The temporal exposure of the Argillite Cut is an important component of the vulnerability as described in section 4.3.3.

B.C. Highway 99 is a single lane highway in each direction characterized by many curves, steep grades and few areas for faster vehicles to pass slower ones. The roadway is used by several groups. Some residents of Squamish commute to and from work in Vancouver. Skiers and outdoors enthusiasts access recreational areas north of Squamish. Sightseers and tourists view the local scenery. Transport trucks use the route to link the industrial and commercial activities in the lower mainland and Squamish and its hinterland. This traffic travels at a wide range of speeds based on the drivers' purposes and familiarity with the road, and the handling and acceleration attributes of their vehicles. The wide variance in vehicle speed and the lack of passing areas produces groups of faster vehicles following slower ones rather than an even traffic distribution. The five vehicles following a bus in figure 5.4 illustrate this point. This increases the population exposed to rock fall related hazard for two reasons. First, the larger the number of vehicles in a group accelerating and decelerating around curves and up and down steep grades the lower the average velocity. This increases the exposure time. Second, closely-spaced vehicles are at a greater risk of collision in the event that a rock fall effects one of the vehicles.

The following is a review of the traffic statistics available for B.C. Highway 99 with respect to exposure time.

5.3.7.1 Traffic Statistics

Available traffic statistics cannot quantify all the effects of traffic flow patterns. It is possible to estimate the number of vehicles traveling through the Argillite Cut based on data collected by the B.C. MOTH Planning Services Branch (1983, 1986, 1989, 1990, 1991, 1992). There are three vehicle count locations within 25 km of the Argillite Cut each with various recording and location limitations.

There has been a count location 0.8 km north of Horseshoe Bay. Prior to 1989 this was a temporary station but it is now a permanent station with the capacity to record traffic volumes per day for every day of the year. This information cannot be used directly for the flow volume through the Argillite Cut because a significant proportion of the traffic north from Horseshoe Bay is traveling to and from the community of Lions Bay, approximately half way between the Argillite Cut and Horseshoe Bay.

There is a count location 0.3 km north of the Woodfibre Ferry Road, south of Squamish but it is a counted for only a temporary period of time during the year. As a result only Summer (July and August) Average Daily Traffic (SADT) volume information is reported for this locality. In addition, the location of the count site 0.3 km North of the Woodfibre Ferry road includes all traffic volume between Squamish and Woodfibre and does not include vehicles traveling between Woodfibre and Horseshoe Bay, through the Argillite Cut.

The third count location is the at the north end of Alberta Creek Bridge (7 km south of the Argillite Cut) towards the north end of the community of Lions Bay. This is the closest count location to the Argillite Cut but the information collected here has severe limitations. First, this location is a special count site meaning that only SADT information is reported for specific years: 1989, 1990 and 1991. Second, although this location is north of most of the community of Lions Bay, up to 10 % of the residences in Lions Bay are accessed via secondary roads off B.C. Highway 99 north of the Alberta Creek Bridge. Third, the recording device used at this location was a pneumatic hose detection device which typically records more than the true number of vehicles. Fourth, although there are no residences between Alberta Beach and the Argillite Cut there are several locations at which sightseers and tourists can turn around and never pass through the Argillite Cut. It is assumed that the number of vehicles that do this is small in relation to the total vehicle flow along Highway 99. Fifth, there are a certain number of vehicles traveling through the Argillite Cut from the north and then returning to the north without ever passing the Alberta Creek location. Sixth, there is the possibility that residents of Lions Bay with access north of the Alberta Creek Bridge may travel north through the Argillite Cut. These highway users would not be counted by the Alberta Creek count location. Lions Bay is primarily a bedroom community for the Greater Vancouver region to the south rather than the area to the north therefore the percentage of the traffic in this last category would be small. Table 5.4 summaries these effects and demonstrates that the Alberta Creek count location can be assumed to represent an upper bound on the number of vehicles traveling through the Argillite Cut.

To obtain the most reliable traffic count through the Argillite Cut the information from the Horseshoe Bay and Alberta Creek count locations are integrated. Using the proportional relation

$$\text{Alta Cr. AADT}_{yr} = \frac{(\text{H. Bay AADT}_{yr})*(\text{Alta Cr. SADT}_{yr})}{(\text{H. Bay SADT}_{yr})} \qquad (A)$$

where the subscript, yr denotes the year of interest. The AADT for Alberta Creek can be estimated for the years that SADT information is available for Alberta Creek.

Using the average of the Horseshoe Bay AADT and SADT data from the three years 1989, 1990, and 1991 and the annual Horseshoe Bay SADT information it is possible to estimate the Horseshoe Bay AADT for previous years using the relation.

$$\text{H. Bay AADT}_{yr} = \frac{(\text{H. Bay SADT}_{yr})*(\text{H. Bay AADT}_{avg})}{(\text{H. Bay SADT}_{avg})} \qquad (B)$$

Substituting (B) into (A) it is possible to estimate the AADT at Alberta Creek for a given year

$$\text{Alta Cr. AADT}_{yr} = \frac{(\text{H. Bay SADT}_{yr})*(\text{H. Bay AADT}_{avg})*(\text{Alta Cr. SADT}_{avg})}{(\text{H. Bay SADT}_{avg})^2}$$

The average daily traffic volume data and estimated AADT for the Argillite Cut is summarized in figure 5.25.

There are several inconsistencies in the methods used to collect the traffic statistics. The following is a brief description of these. In the their 1980 - 1983 publication, MOTH (1985) indicates that the SADT data from the Horseshoe Bay count station is based on

> A short count of at least 24 hours duration is compared to the counter for the same period at a permanent count station and expanded to a July-August average daily volume. The accuracy of these results depends upon the location of the permanent station in relation to the short count station and the correlation of defined traffic patterns. (p. i)

MOTH (1986, p. i) stated that the short counts used to estimate the SADT information were "... of at least four days duration...". In MOTH (1987, p. i) this was increased to "A short counts of at least seven days duration...". MOTH (1987, p. ii) also noted that

> Traffic volumes recorded include all types of motorized vehicles; however, some of the lighter ones such as motorcycles may not be detected on all occasions.

MOTH (1988, p. i) stated that SADT traffic

> Volumes are recorded in 15 minute increments for approximately seven days (short count) or for the entire year (permanent counts) and are compiled as Summer Average Daily Traffic Volumes where summer is defined as being the months of July and August"

This has remained the procedure for all count sites since 1988. MOTH (1988, p. ii) also commented on their detection methods.

> A number of counts in section I, II and III were obtained by use of a pneumatic hose or road tube detector system which requires that every two axles be recorded as one vehicle. In counts of this type, no compensation was made for the over count caused by recording vehicles with more than two axles. Other counts were obtained by use of an induction loop detection system which allows all vehicles to be recorded singly, regardless of the number of axles. Thus, if counts on hose and loop detectors were taken at simultaneously at the same location, the former would probably indicate a higher volume than the latter.

In 1989 (MOTH 1989) the Horseshoe Bay count location became permanent and as a result data is available for every day of the year.

The B.C. (MOTH 1991, p. iv) publication indicated that "The information [for SADT location] produced is presented as an estimate average daily traffic volume for the month of July and August rounded to the nearest fifty or hundred vehicles.

In conclusion figure 5.25 indicates a reduction in SADT traffic at the Horseshoe Bay in 1989. This is undoubtedly the result of the change in counting system from pneumatic to induction loop detection systems. It may also reflect the improved accuracy of measuring traffic flow throughout the year. I would therefore conclude that the traffic volumes prior to 1989 are high and those from 1989 to the present are more reliable.

5.4. Risk calculations

The societal and individual probability of a death caused by a rock fall while in the Argillite Cut can be calculated using the procedures outlined in section 4.5. The lower bound calculations of each of the three cases are completed in sections 5.4.1 - 5.4.3. These calculations are based on the 9 rock fall events recorded in the Argillite Cut during the 4.1 years that Capilano Highway Services Limited systematically recorded rock falls. A summary of the upper and lower bounds and best estimates is included in section 5.4.4. It is assumed that these rock fall frequencies are representative of the early 1980s when the Just incident occurred.

5.4.1 Stationary vehicle/falling rock

The Just case is an example of a stationary vehicle and a falling rock. Just's car was stopped in a line of traffic when a rock impacted directly on the car killing his daughter and disabling the Just. Although not mentioned in any of the legal decisions pertaining to this case (Donald J. 1991, Cory J. 1989, Hinkson J. 1986, and McLachlin J. 1985) it is assumed that the car was stopped for less than half an hour. Since Just was waiting in a "line of traffic" (Donald J. 1991, p. 213) it is assumed that the average distance between vehicles was 1.5 metres. The annual probability of a rock hitting a vehicle stopped in the Cut for half an hour is:

$$\begin{aligned} P(S{:}H) &= (L_v - S_V) / Lv && (4.8)\\ &= (5.4 - 1.5) / 5.4 \\ &= 0.72 \end{aligned}$$

$$\begin{aligned} P(S) &= 1 - (1 - P(S{:}H))^{Nr} && (4.4)\\ &= 1 - (1 - 0.72)^{2.2} \\ &= 0.940 \end{aligned}$$

$$\begin{aligned} P(T{:}S) &= t / 8760 && (4.10)\\ &= 0.5 / 8760 \\ &= 5.7\ 10^{-5} \end{aligned}$$

$$\begin{aligned} P(A) &= P(T{:}S) * P(S) && (4.11)\\ &= 0.940 * 5.7\ 10^{-5} \\ &= 5.4 * 10^{-5} \end{aligned}$$

Therefore the probability that one of the vehicles in the Cut is hit by a rock fall is one in 19,000.

The probability of a rock hitting an individual's vehicle, PAV in the Cut is

$$\begin{aligned} P(S{:}H) &= L_V / L_C && (4.12)\\ &= 5.4 / 476 \\ &= 0.011 \end{aligned}$$

$$\begin{aligned} P(S) &= 1 - (1 - P(S{:}H))^{Nr} && (4.4)\\ &= 1 - (1 - 0.011)^{2.2} \\ &= 0.025 \end{aligned}$$

$$\begin{aligned} PAV &= P(S) * P(T{:}S) && (4.7)\\ &= 0.025 * 5.7\ 10^{-5} \\ &= 1.4 * 10^{-6} \end{aligned}$$

The hazard to a stationary vehicle and a line of stationary vehicles in the Cut, assuming a half hour delay is an annual occurance, is calculated for the upper and best estimate rock fall frequencies. The results are included in Table 5.5

5.4.2 Moving vehicle/falling rock

Following the procedure described in section 4.5.1 using

N_V = 4800 vehicles per day for 1981, L_V = 5.4 m (Chrest et al. 1989), and V_V = 80 km/hr

$$\begin{aligned} P(S{:}H) &= N_V * L_V / 24000 / V_V && (4.1)\\ &= 4800 * 5.4 / 24000 / 80 \\ &= 1.35 * 10^{-2} \end{aligned}$$

$$P(S) = 1 - (1 - P(S{:}H))^{Nr} \quad (4.4)$$
$$= 1 - (1 - 0.0135)^{2.2}$$
$$= 2.95 * 10^{-2}$$

The probability of an individual being in an accident, PAV, is also calculated.

$$P(S{:}H) = L_v / L_c \quad (4.5)$$
$$= 5.4 / 479$$
$$= 1.1 * 10^{-2}$$
$$P(S) = 1 - (1 - P(S{:}H))^{Nr} \quad (4.4)$$
$$= 1 - (1 - 0.011)^{2.2}$$
$$= 2.4 * 10^{-2}$$
$$P(T{:}S) = L_c / V_v / 8{,}760{,}000 \quad (4.6)$$
$$= 5.4 / 80 / 8{,}760{,}000$$
$$= 7.7 * 10^{-9}$$
$$PAV = P(S) * P(T{:}S) \quad (4.7)$$
$$= 0.024 * 7.7 * 10^{-9}$$
$$= 1.8 * 10^{-10}$$

The hazards using the upper bound and best estimate based on the asphalt impact mark mapping are tabulated in Table 5.5.

5.4.3 Moving vehicle/fallen rock

This situation is the most common but as previously mentioned the number of rocks on the road that are large enough to effect a vehicle is only a fraction of the total number of rocks that reach the road. At a vehicle speed of 80 kmph the decision sight distance, L_{dsd} is 250 m (AASHTO 1990, Table III-3).

$$P(S{:}H) = N_v * L_{dsd} / 48000 / V_v \quad (4.13)$$
$$= 4800 * 250 / 48000 / 80$$
$$= 0.313$$

Therefore a driver's decision sight distance occupies P(S:H) of the road at any given time. The methodology derived in 5.1.1 can now be used assuming that N_r includes only those rocks larger than 15 cm in diameter. From section 5.4.1 $N_r = 2.2$.

$$P(S) = 1 - (1 - P(S{:}H))^{Nr} \quad (4.4)$$
$$= 1 - (1 - 0.313)^{2.2}$$
$$= 0.561$$

The probability of an individual being in an accident, PAV is calculated for this case as well.

$$\begin{aligned} P(S{:}H) &= L_{dsd} / 2 / L_c && (4.14) \\ &= 250 / 2 / 479 \\ &= 0.261 \\ P(S) &= 1 - (1 - P(S{:}H))^{Nr} && (4.4) \\ &= 1 - (1 - 0.261)^{2.2} \\ &= 0.486 \\ P(T{:}S) &= L_{dsd} / V_v / 8{,}760{,}000 && (4.15) \\ &= 250 / 80 / 8{,}760{,}000 \\ &= 3.57\ 10^{-7} \\ PAV &= P(S) * P(T{:}S) && (4.7) \\ &= 0.486 * (3.57 * 10^{-7}) \\ &= 1.7 * 10^{-7} \end{aligned}$$

The number of rock fall impact marks for all impacts greater than 15 cm diameter both outside and within the fog line is the same as the reported number of rock falls. Therefore the upper bound and best estimate results are not included in Table 5.5.

5.4.4 Summary

The probability of a rock fall accident in the Argillite Cut is summarized in Table 5.5 based on traffic volumes of 4800 vehicles per day at the time of the Just Case in 1982.

It is evident that the probability of one or more accidents occurring for a stationary line of vehicles is insensitive to the number of rock falls. This is because the high spatial probability of a vehicle being hit causes the P(A) to rapidly approach unity as the number falls per year increases. Therefore the probability of one or more vehicle being impacted is equal to the fraction of time the Cut is occupied.

Table 5.2 contains one record of a rock fall causing damage to a vehicle on April 11, 1991. It is assumed that this was the result of a car hitting fallen rock. Based on this interpretation of the CHSL records the probability of a moving vehicle/fallen rock accident is less than $2.4 * 10^{-1}$ per year. This is lower than the estimated P(A) of $5.1 * 10^{-1}$ per year but of the same order of magnitude. There may also be incidents that are not recorded by CHSL.

To estimate the return period of a fatality due to rock fall the following assumptions were made. For all three cases it is assumed that a rock with sufficient energy to deform the asphalt would penetrate the skin of an automobile and could seriously injure or kill one or more occupants. Therefore the rock fall frequencies estimated using the rock fall impact mapping are applicable.

In the case of the stationary vehicles the probability of death given temporal impact, P(L:T) is assumed to be less than 1 in 8. This is based on the approximation that no more than a quarter of the length of an average vehicle is occupied by passengers. In addition, it is assumed that given the distribution of rock fall sizes no more than one of every two falls that impact a person will result in death.

For the moving vehicle/falling rock case a P(L:T) of 1 in 5 is assumed. The P(L:T) is higher than that for a stationary vehicle because in addition to the possibility of direct impact with the passengers, it must account for the detrimental effect a rock could have on the performance of a vehicle. For example, the driver could lose control of the vehicle increasing the probability of a fatality.

In the moving vehicle/fallen rock case a P(L:T) of 1 in 10 is assumed. This lower P(L:T) is used to account for the cases where the driver of the vehicle is aware of the fallen rock. In this situation the driver should be able to minimize the probability of a fatality to some extent.

The combination of these P(L:T) estimates with the probability of an accident to the exposed population, and the probability of an individual being in an accident using the best rock fall frequencies are summarized in Table 5.6. Also included are PDI for different usage levels an the sum of the PDIs and P(D) for the two moving vehicle cases.

Zone	A		B		C		D		E		F		Entire cut	
	value	score	value	score	value	score	value	score	value	score	value	score	value	score
Slope height (m)	33	100	70	100	23	28	36	100	100	100	40	100	100	100
Ditch effectiveness		27		27		27		27		27		60		27
Slope length (m)	65		75		45		15		100		180		480	
Average vehicle risk	30	4	35	5	21	3	7	1	47	8	84	41	225	100
Sight distance (m)	105		100		105		105		110		110		105	
Percent sight distance	42	73	40	81	42	73	42	73	44	65	44	65	42	73
Road width (m)	9.5	17	9.5	17	9.5	17	9.5	17	9.5	17	9.5	17	9.5	17
Geology Structure		27		60		27		81		60		40		60
Friction		27		9		27		27		9		27		27
Block size (m)	1.0	35	1.0	35	0.6	8	0.3	3	1	35	0.6	8	1	35
Climate		27		27		27		27		27		27		27
Rock fall history		9		40		9		40		18		50		27
Total		**346**		**381**		**245**		**394**		**367**		**402**		**493**

The posted speed limit is 80 km/h resulting in a decision sight distance of 250 metres. The average traffic flow was 4,800 cars per day in 1982.

Table 5.1 RHRS results for the Argillite Cut on B.C. Highway 99

Table 5.2 Maintenance and rock fall history of the Argillite Cut

Date			time	Loc (km)	Volume (m^3)	notes
		1954-55				First contracts for the Alberta Bay to Porteau 12.6 km (7.91 miles) section were let. (MOH 1955)
		1955-56				Section cleared, drainage and grading started. (MOH 1956)
Mar	31	1958				83 % complete. (MOH 1958)
Mar	31	1959				Alberta Bay to Porteau 100 % complete. (MOH 1959)
Feb		1969			6000	Four day closure, (Fieber 1990). Rock fall volume of 5700 m^3 (Nasmith 1976)
Jan		1971		21.5	700	(Fieber 1990). Rock fall volume of 75 m^3 (Nasmith 1976)
Aug		1971			700	(Fieber 1990). Rock fall volume of 750 m^3 (Nasmith 1976)
		1972				Argillite was scaled, 90 m^3 mesh reinforced shotcrete applied to argillite, horizontal drains installed. (Fieber 1990). Shotcreted area 9200 m^2 7.5 cm thick (Nasmith 1976)
Jan	16	1982	9:00	21.5	3	Snow storm, Just incident, (Hungr 1989, Fieber 1990, Donald J. 1991))
		1982		21.4-.5		30 m^3 scaled. (MOTH 1982)
		1982		21.5-.6		Scaled. (MOTH 1982)
Jan		1984		21.7	40	(MOTH 1988)
Sep		1985		21.7	10	Probably the same as the next one, (MOTH 1988).

Table 5.2 continued

Date			time	Loc (km)	Volume (m^3)	notes
Sep		1985		22.5		(MOTH 1988)
Oct Dec	26- 16	1987			0	1901 man hours scaling, 802 m^3 or rock removed, 414 linear metres of rock bolting. (Seelig 1993)
Mar		1989				Latest date for re-paving. (Bartle 1993 and Jonat 1993)
Jan	29	1989	9:30	21.5	1	Rocks cleared by W.V. 31, one lane blocked. (CHSL)
Jan		1989		21.8	1	(Fieber 1990.) (may be same as Jan 29, 1989, CHSL)
Mar	21	1989	5:05	19.4-23.4		Rocks on highway, 2 km N to 2 km S of Bertram Creek, W.V. 31 cleared rocks, 25 minutes to clear. (CHSL)
May	4	1990	6:13	21.7		3 km south Porteau, Rocks on southbound lane, R 1 reported, Advised WV 10 CAP 10 cleared. (CHSL)
Sep		1990		21.6	1	one lane blocked.
Sep		1990		21.5	1	(Fieber 1990) (may be same as Sep, 1989, CHSL).
Dec	18	1990		17.2-21.4		Between Deeks and Bertram creeks, Rock on road, W.V. cleared rocks in 6 minutes. (CHSL)
Dec	19	1990		22.2		Tree on road (CHSL)
Mar	28	1991	3:28	21.6		4.5 km N Deeks Creek, Fallen rock, W.V. 10 cleared away rocks in 14 minutes, one lane blocked. (CHSL)
Apr	11	1991	7:37	21.5	<1	Minor slide, R 1 reported rocks on road, SQ 11 cleared in 35 minutes (one vehicle damaged), one lane blocked (CHSL)

Table 5.2 continued

Date			time	Loc (km)	Volume (m^3)	notes
Jul	15	1991	20:44	22.5		Kallahne Creek, Rocks on road, Reg reported, SQ 10 cleared in 40 minutes. (CHSL)
Jan	9	1992	2:05		<.5?	Bertram Creek, N and S bound debris, W.V. 20 reported and cleared rocks. (CHSL)
Mar	8	1992	14:42		<.5?	Bertram Creek, Squamish RCMP reported, NV. 10 found nothing. (CHSL)
Apr	8	1992	6:55		0	Bertram Creek, Possible dangerous tree, R 1 reported. Squamish 10 advised. (CHSL)
Jul	10	1992	6:00	21-21.5	<.5	between PGE viewpoint and Brunswick Point, location uncertain. Rock in ditch. (MOTH 1992)
Jul	15	1992	13:39	22	<.5	North bound. Rock on road. WV 10 cleared by 13:39. (CHSL)
Sep	9	1992	10:15	22.0	<1	North portion of Argillite Cut. Source 60 m above road. (MOTH 1992)
Nov	24	1992	9:26	20.9	<.5	500 m S of Bertram Creek, Rock on road, W.V. 30 attended and cleared in 18 minutes. (CHSL)
Dec	31	1992			0	End of survey of CHSL records. (Bartle 1993)

Location	Rainfall (mm)	date yy/mm/dd	Snowfall (cm)	date yy/mm/dd	Years of record
Britannia Beach	121.9	21/10/28	45.7	43/01/19	1912-1974
Squamish	111.8	63/12/22	66.0	66/01/15	1959-1970
Squamish FMC Chemicals	186.0	81/10/30	50.8	75/01/11	1968-1983
Lions Bay	109.2	91/02/02	n/a		1983/07 - 1986/01 1986/11 - 1991/11

Table 5.3 Greatest rainfall on any one observation day near the Argillite Cut to the end of 1991

		Over estimate	Under estimate	Accounted for by Normalized with H. Bay data
1.	Summer count location	X		
2.	Lions Bay north residence	X		
3.	Pneumatic hose	X		
4.	Non continuing south traffic	X		
5.	Non continuing north traffic		X	offset by 4
6.	Lions Bay north residence traveling north		X	more than offset by 2

Table 5.4 Factors affecting traffic flow at the Argillite Cut compared to those recorded at Alberta Creek

Table 5.5 Probability of an accident at the Argillite Cut

Type of incident resulting in accident		Rock fall frequency	
marks	Reported rock falls marks	Best estimate from rock	Total rock
Rock fall/year	2.2	9.1	15.4
Stationary vehicle falling rock			
P(A) (/0.5 hr stop)	$5.4*10^{-5}$	$5.7*10^{-5}$	$5.7*10^{-5}$
PAV (/0.5 hr stop)	$1.4*10^{-6}$	$5.6*10^{-6}$	$9.1*10^{-6}$
Moving vehicle / falling rock			
P(A) (/yr)	$2.9*10^{-2}$	$1.2*10^{-1}$	$1.9*10^{-1}$
PAV (/trip)	$1.7*10^{-8}$	$6.7*10^{-8}$	$1.1*10^{-7}$
Moving vehicle fallen rock			
P(A) (/yr)	$5.1*10^{-1}$		
PAV (/trip)	$4.5*10^{-7}$		

Table 5.6 Probability of fatality at the Argillite Cut

Type of incident resulting in fatality	P(L:T)	P(D) (yr^{-1})	Return Period	PDI (per trip)	(per 500 trips)
Vehicle stationary for half an hour falling rock	0.125	$7.1*10^{-6}$		$7.0*10^{-7}$	
Moving vehicle / falling rock	0.2	$2.3*10^{-2}$	43	$1.3*10^{-8}$	$6.7*10^{-6}$
Moving vehicle / fallen rock	0.1	$5.1*10^{-2}$	18	$4.8*10^{-8}$	$2.2*10^{-5}$
Sum of moving vehicle / falling and fallen rock		$7.4*10^{-2}$	13	$6.1*10^{-8}$	$3.1*10^{-5}$

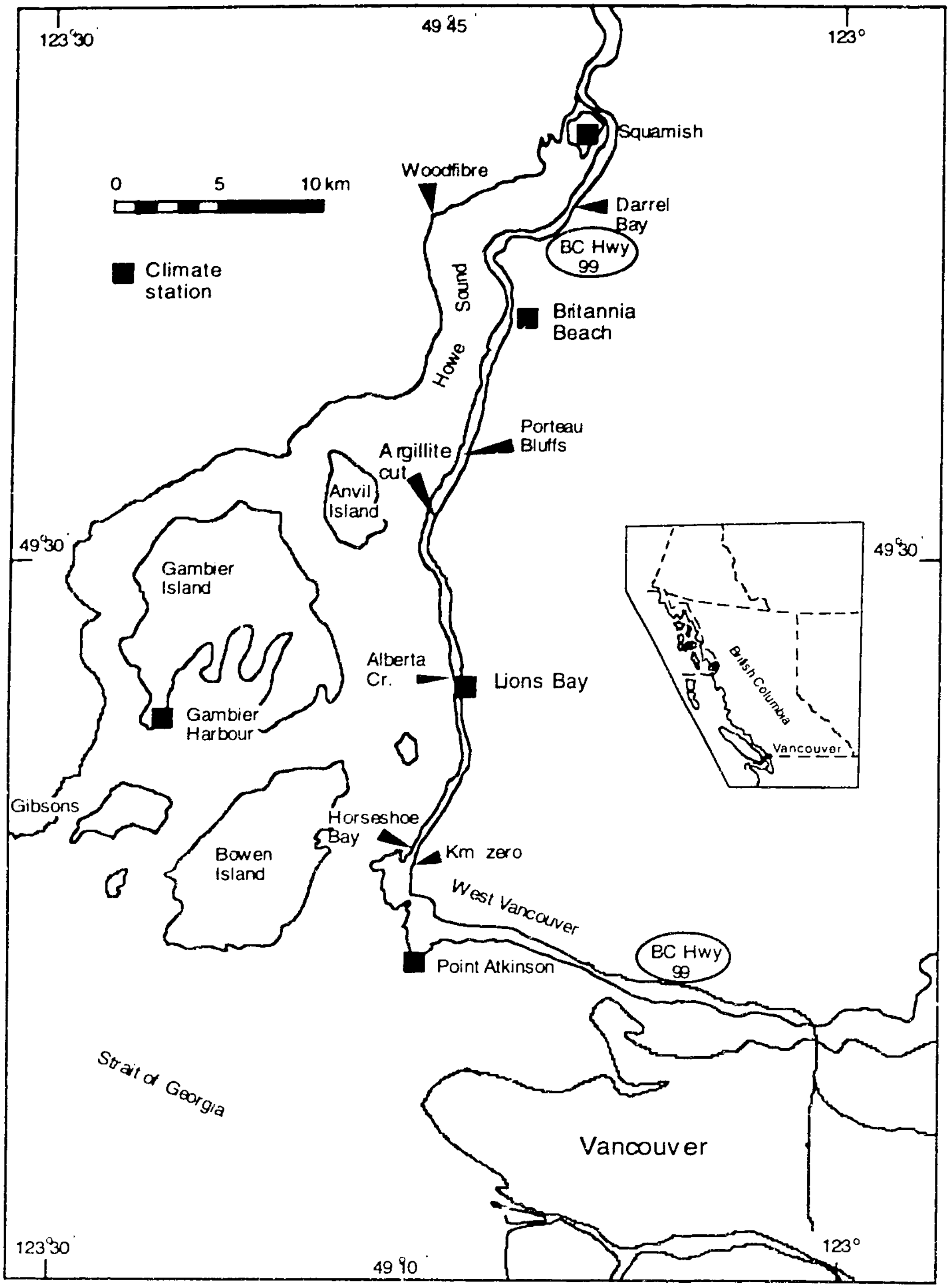


Figure 5.1 Map of Howe Sound showing the location of the Argillite Cut and surroundings with inset map of B.C.

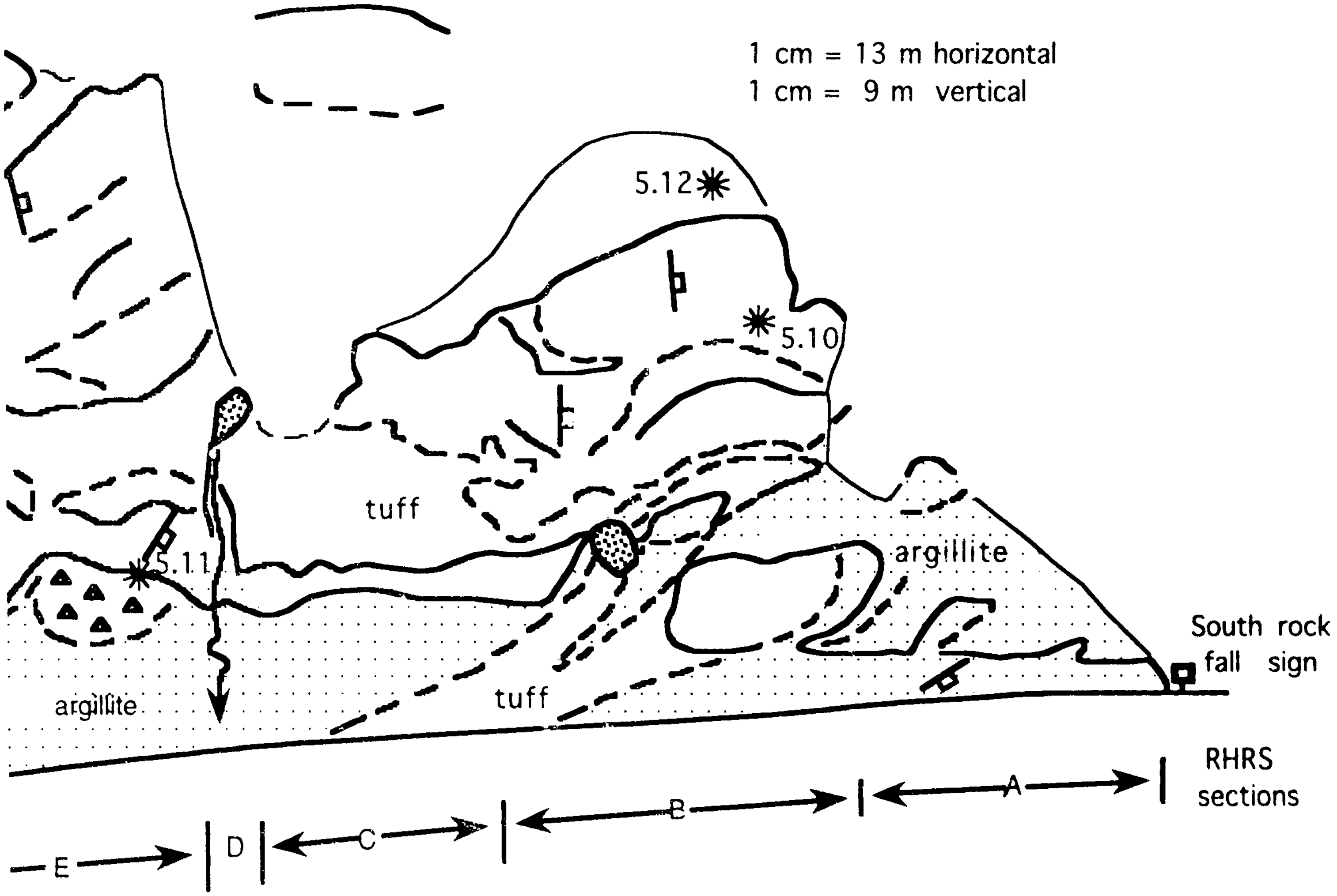


Figure 5.2 Geology of the southern half of the Argillite Cut

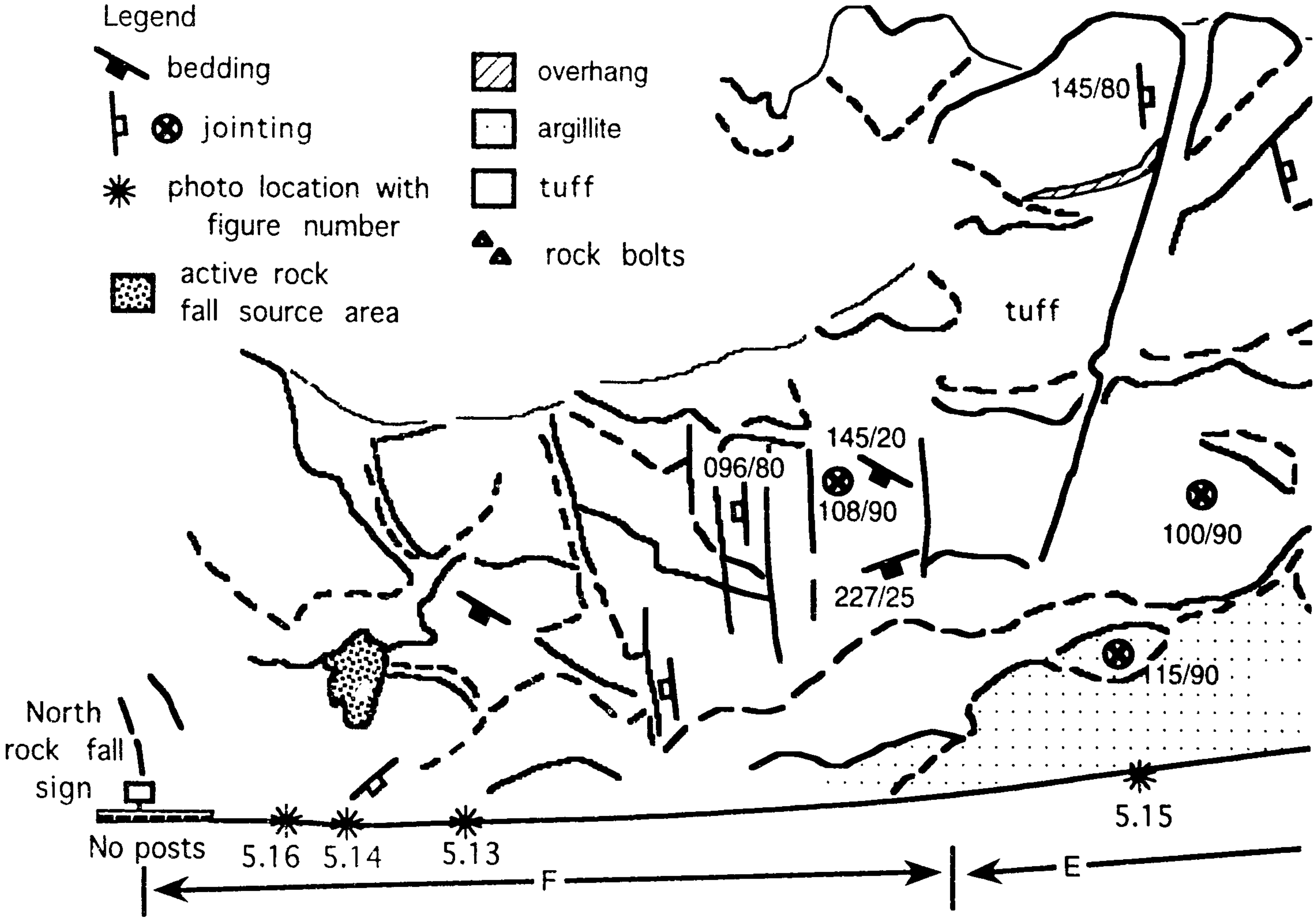


Figure 5.3 Geology of the northern half of the Argillite Cut

Figure 5.4 Oblique aerial photo collage parallel to Argillite Cut from the south.

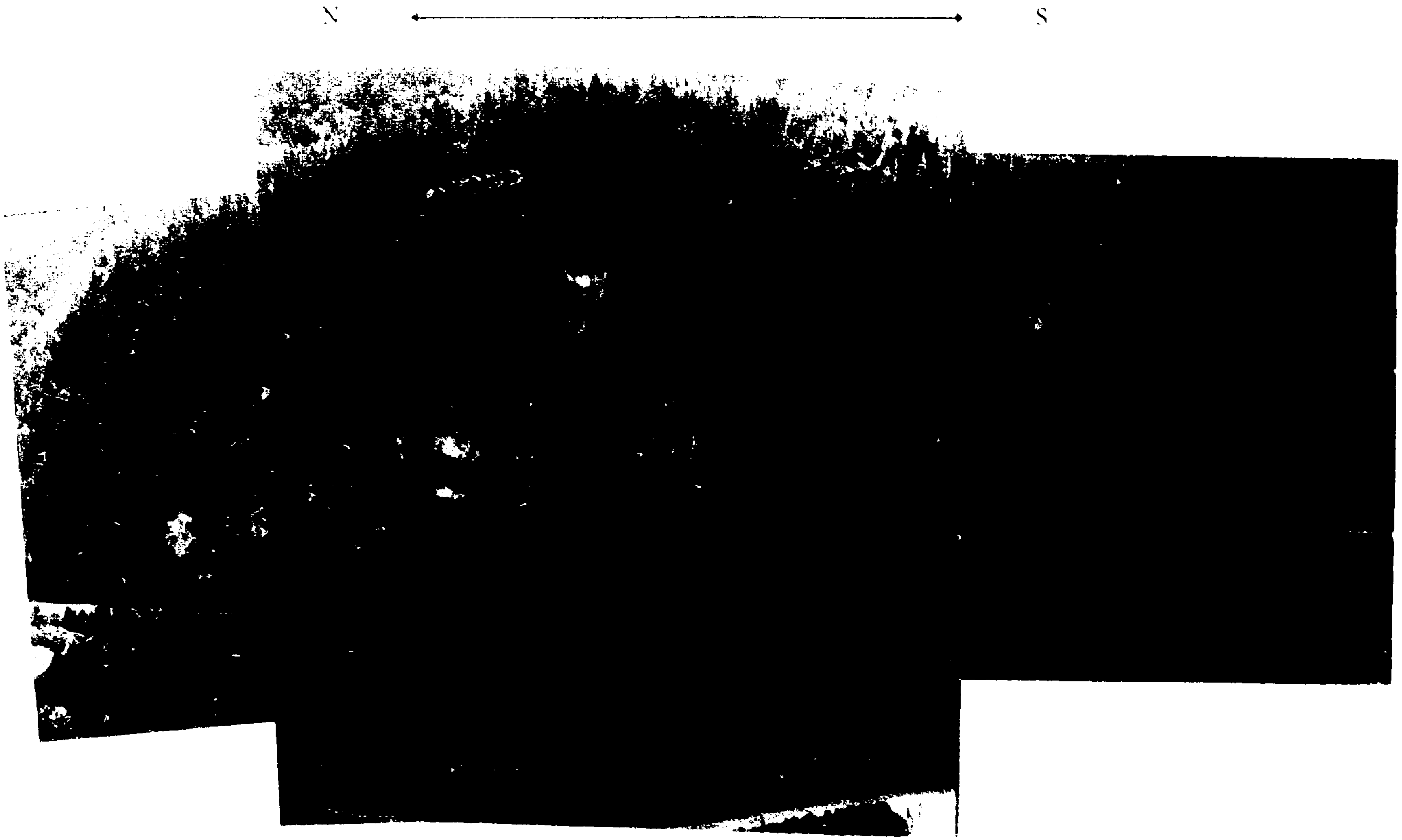


Figure 5.5 Oblique aerial photo collage perpendicular to the Argillite Cut from the west

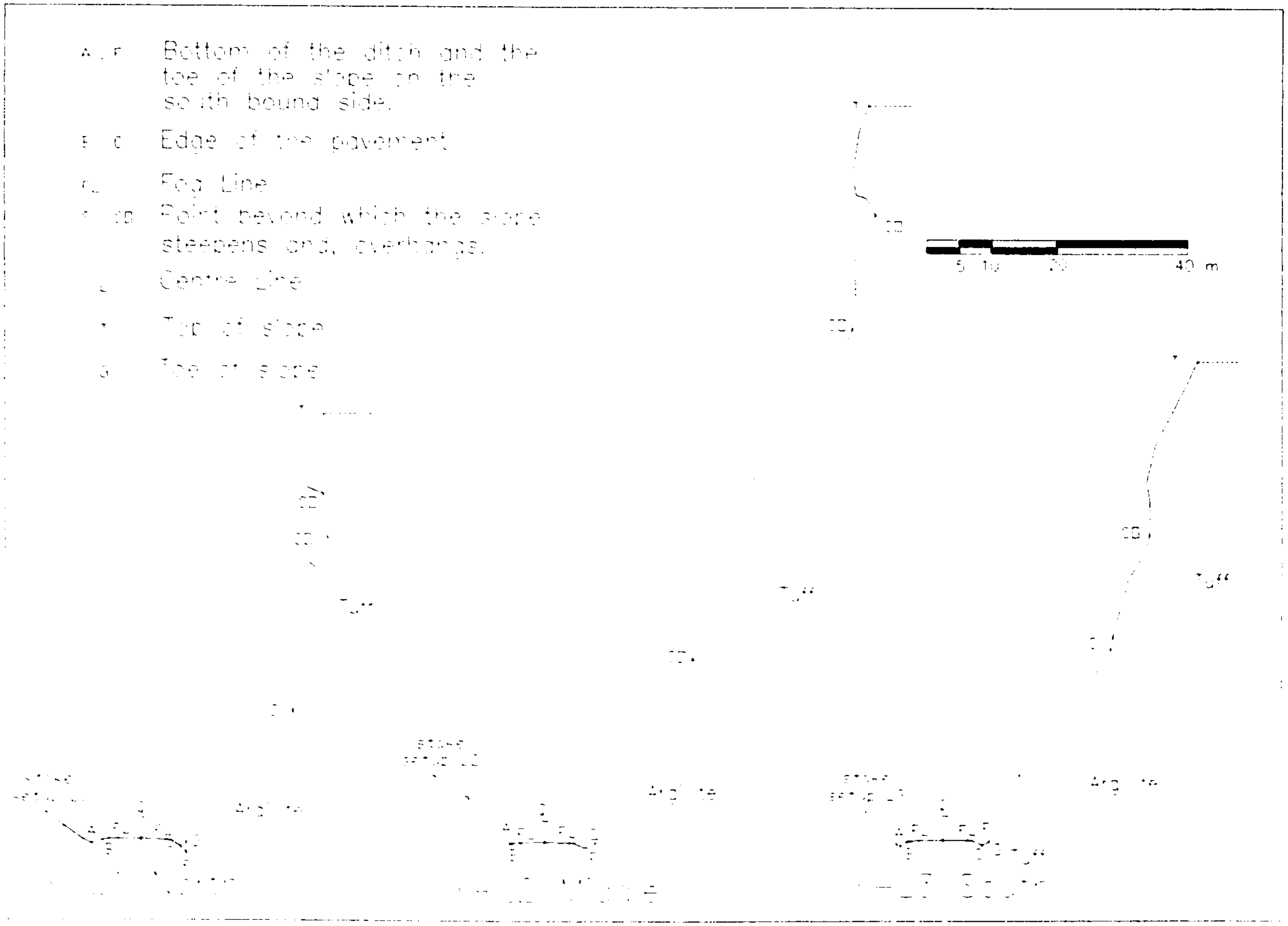


Figure 5.6 Cross sections X-L1, X-L2 and X-L3 through the Argillite Cut

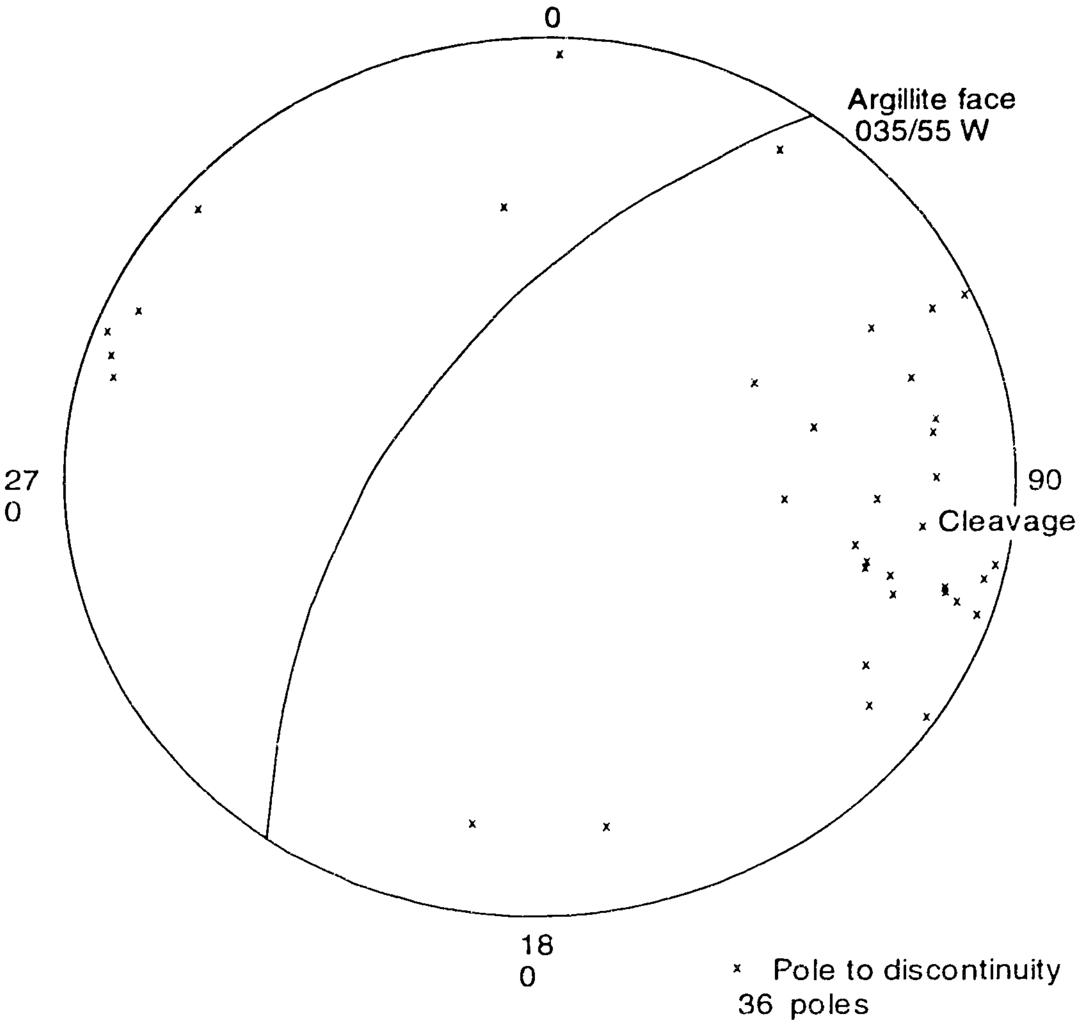


Figure 5.7 Equal area stereonet of discontinuities in the Argillite Cut argillite

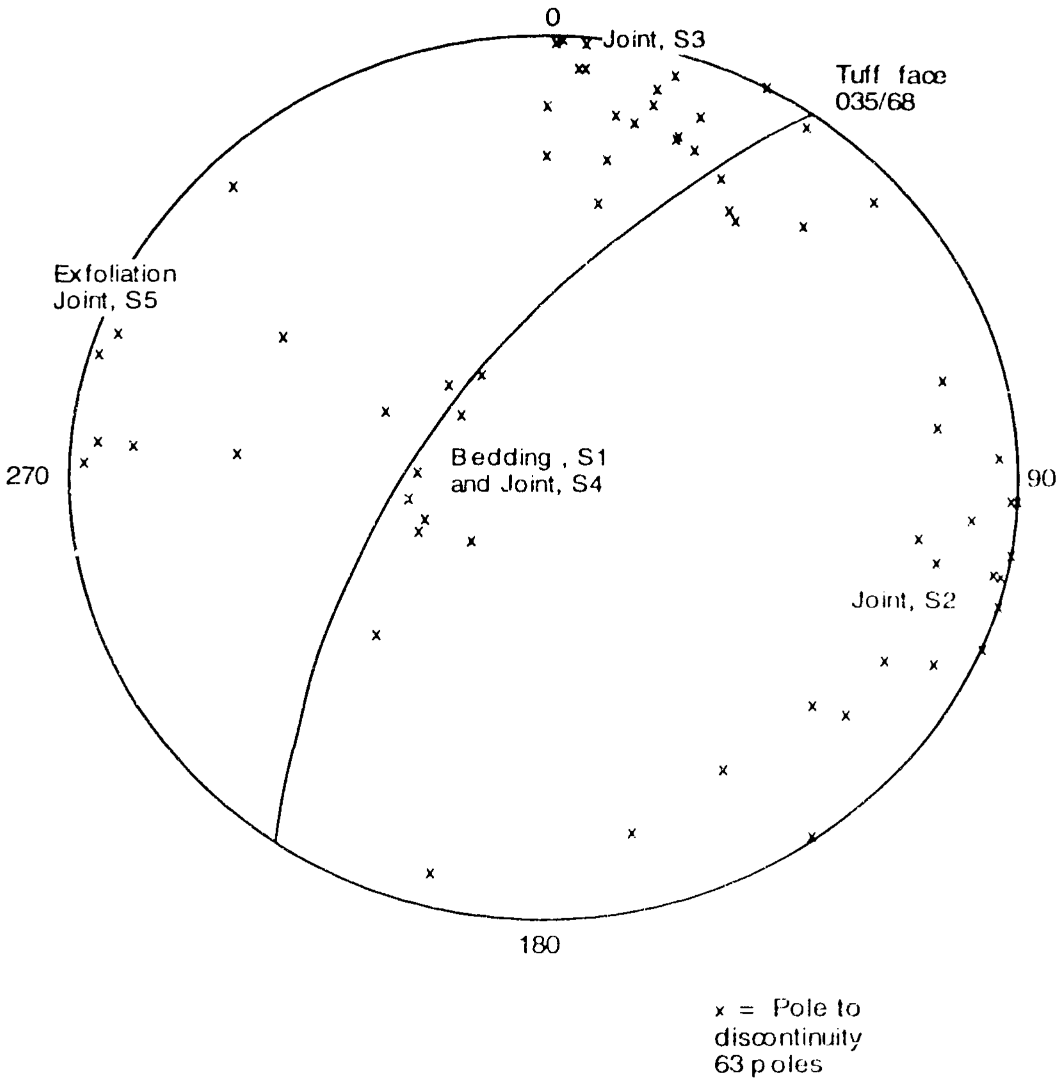


Figure 5.8 Equal area stereonet of discontinuities in the Argillite Cut tuff

Figure 5.9 Photo of a typical tuff/tuff contact and tree growing above a vertical joint

Figure 5.10 Photo of a portion of the argillite/tuff contact with close jointing at the Argillite Cut

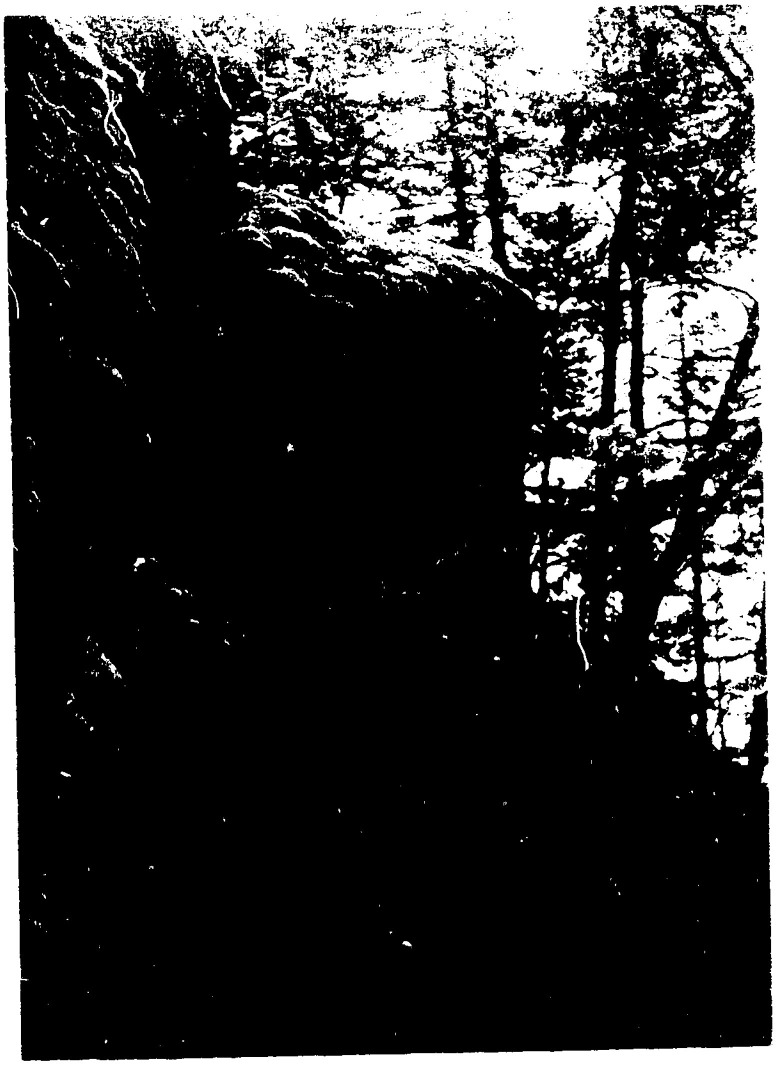


Figure 5.11 Photo of loose block bounded by vertical and daylighted exfoliation joint in tuff above the Argillite Cut

Figure 5.12 Photo of rock fall mark in the south bound lane, 61 metres south of the south bound rock fall sign

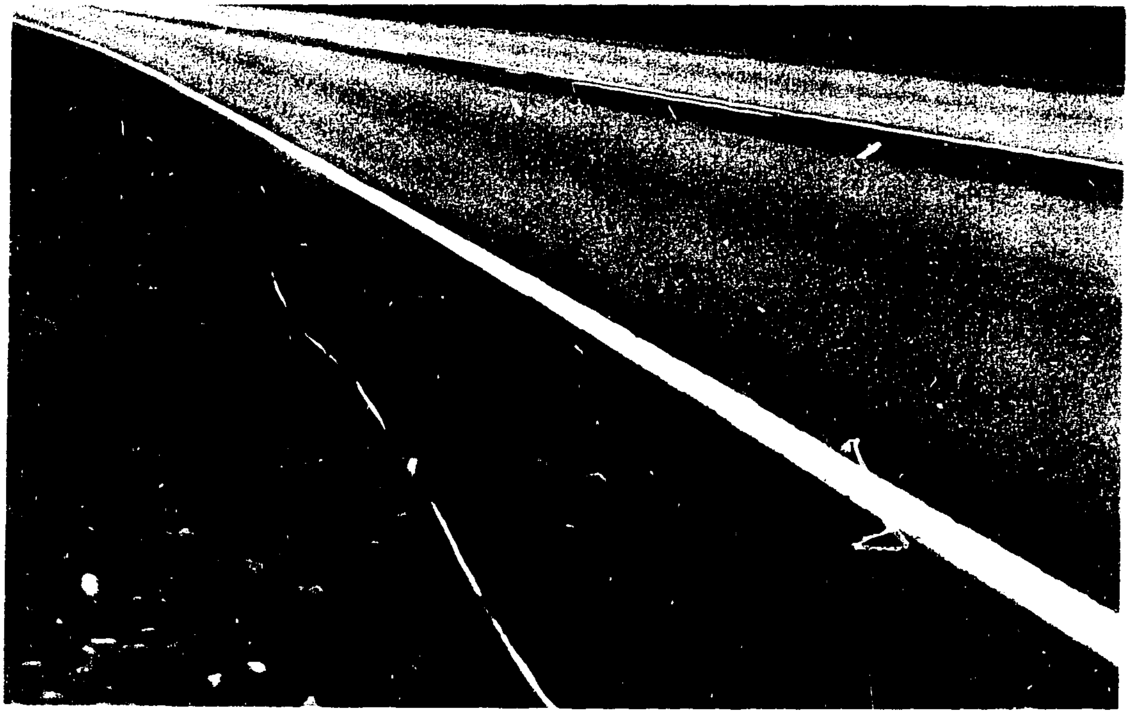


Figure 5.13 Photo of rock fall marks and debris on the north bound lane, 45 metres south of south bound rock fall sign

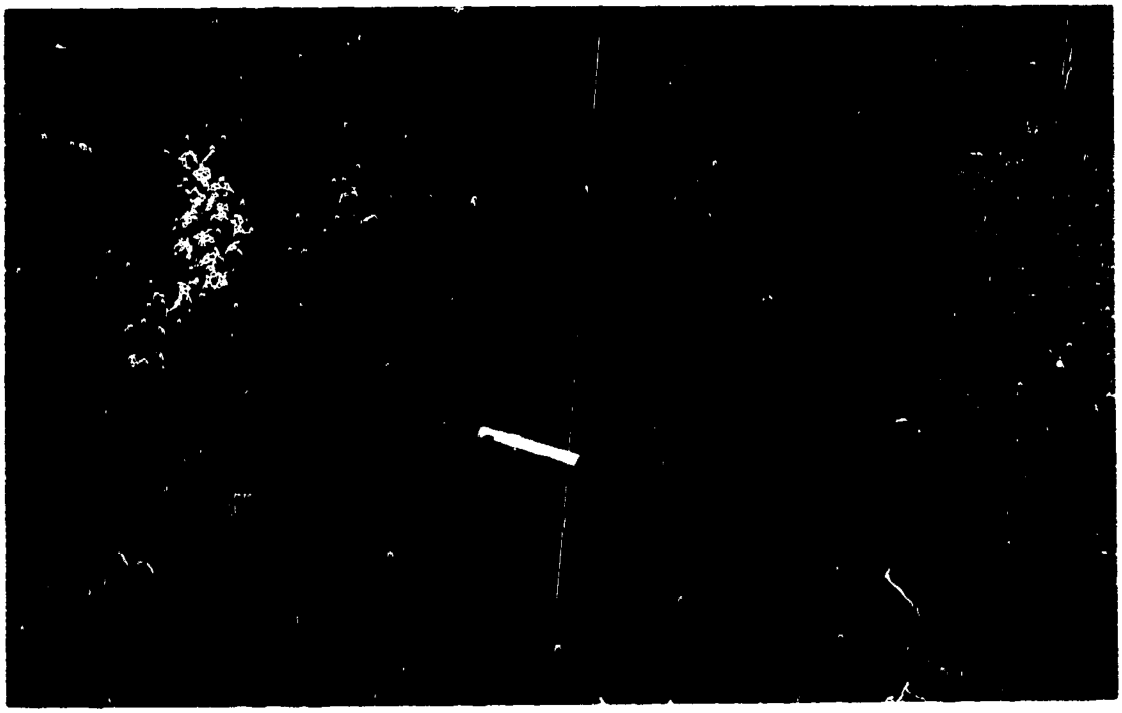


Figure 5.14 Photo of anthropogenic impact mark, 264 metres north of the north bound rock fall sign

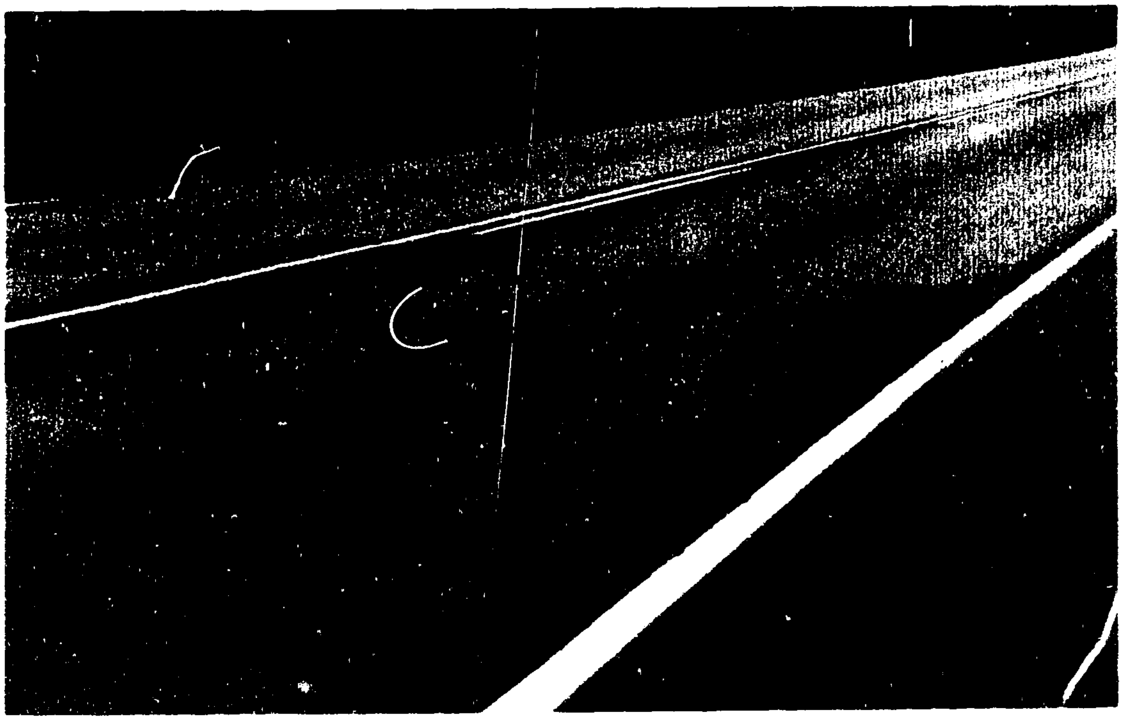


Figure 5.15 Photo of northern limit of 1989 asphalt, 41 metres south of the south bound rock fall sign

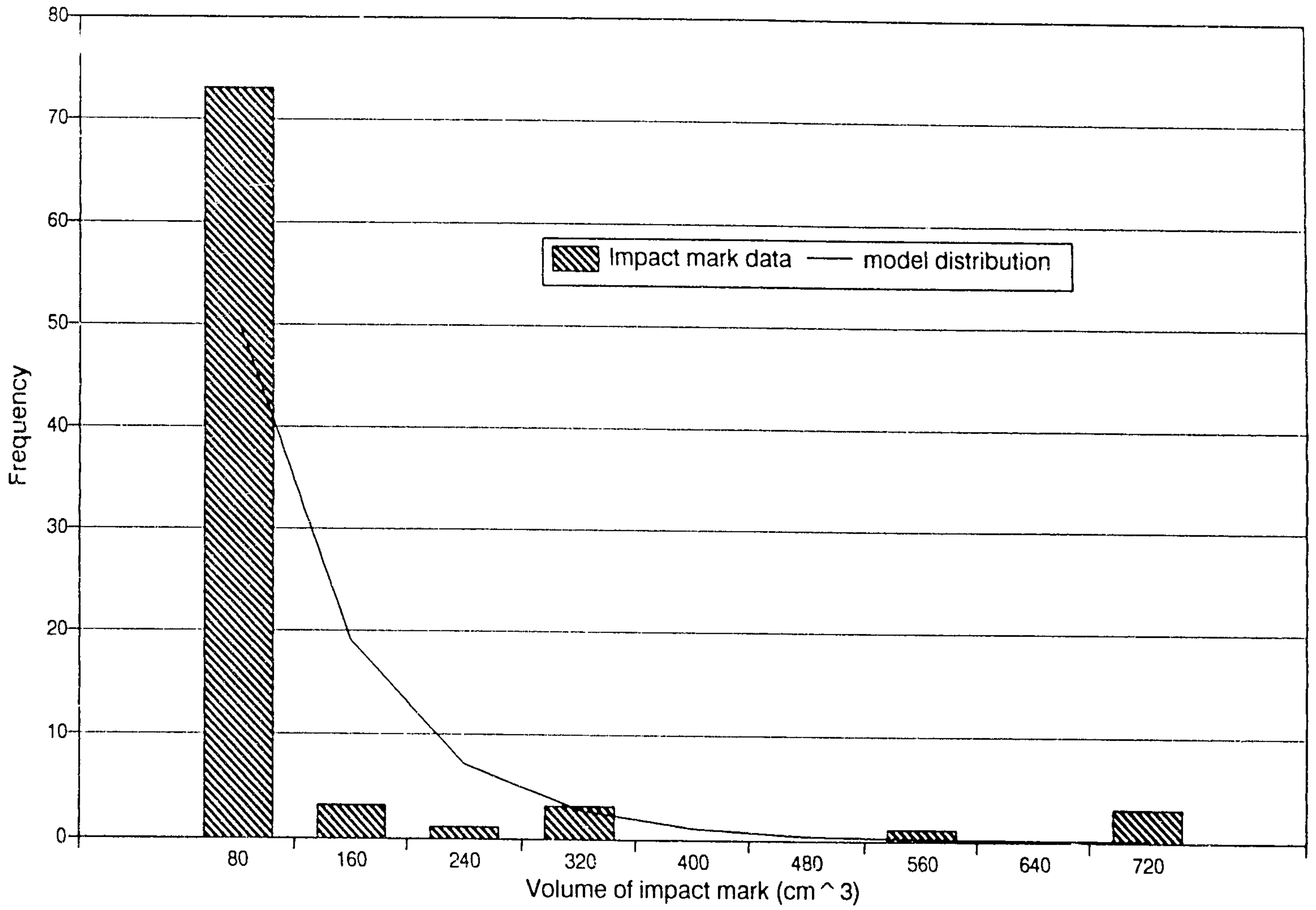


Figure 5.16 Frequency of rock-fall impact-mark volume in the Argillite Cut

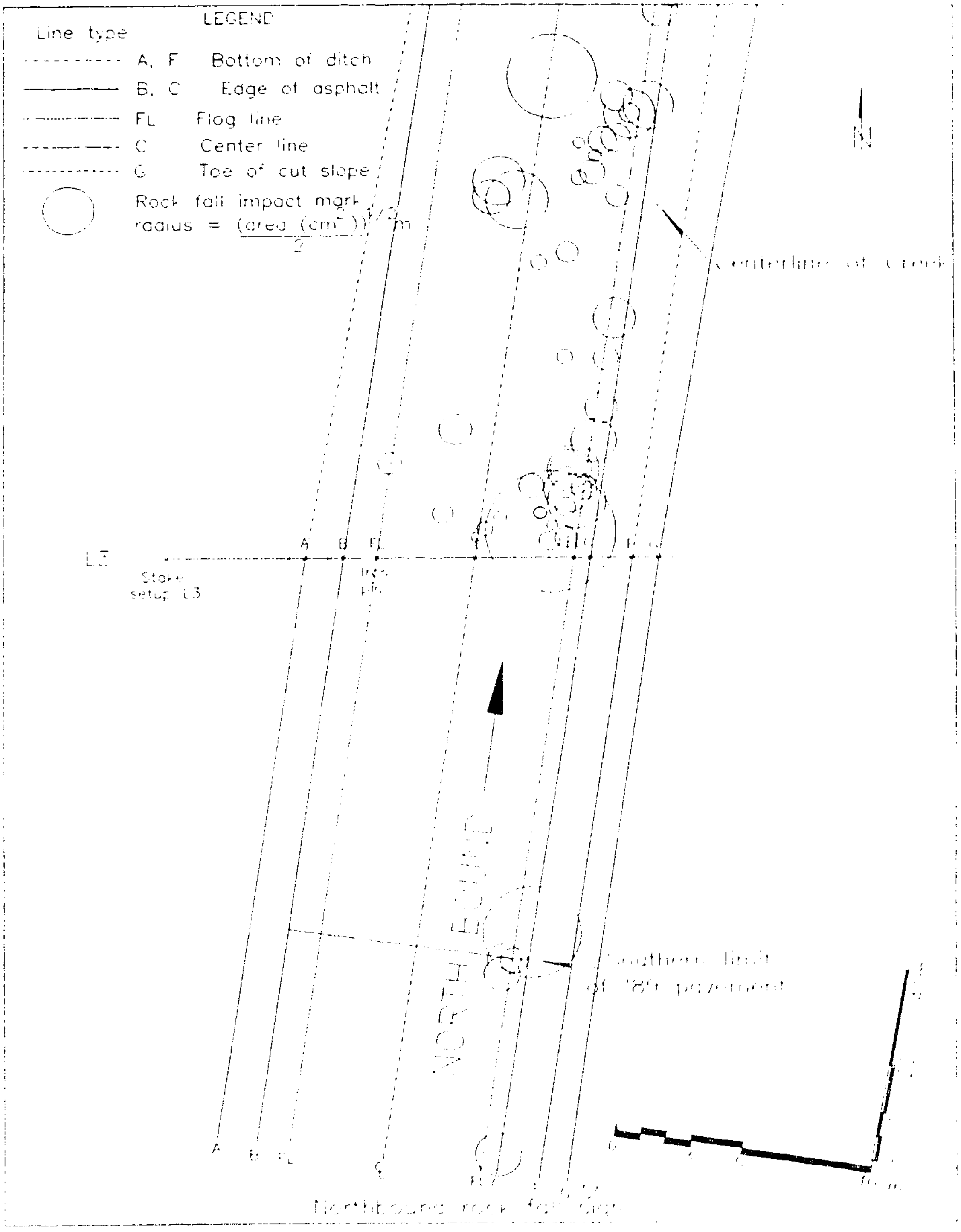


Figure 5.17 Mapping of the rock fall impact marks in the asphalt of the southern half of the Argillite Cut

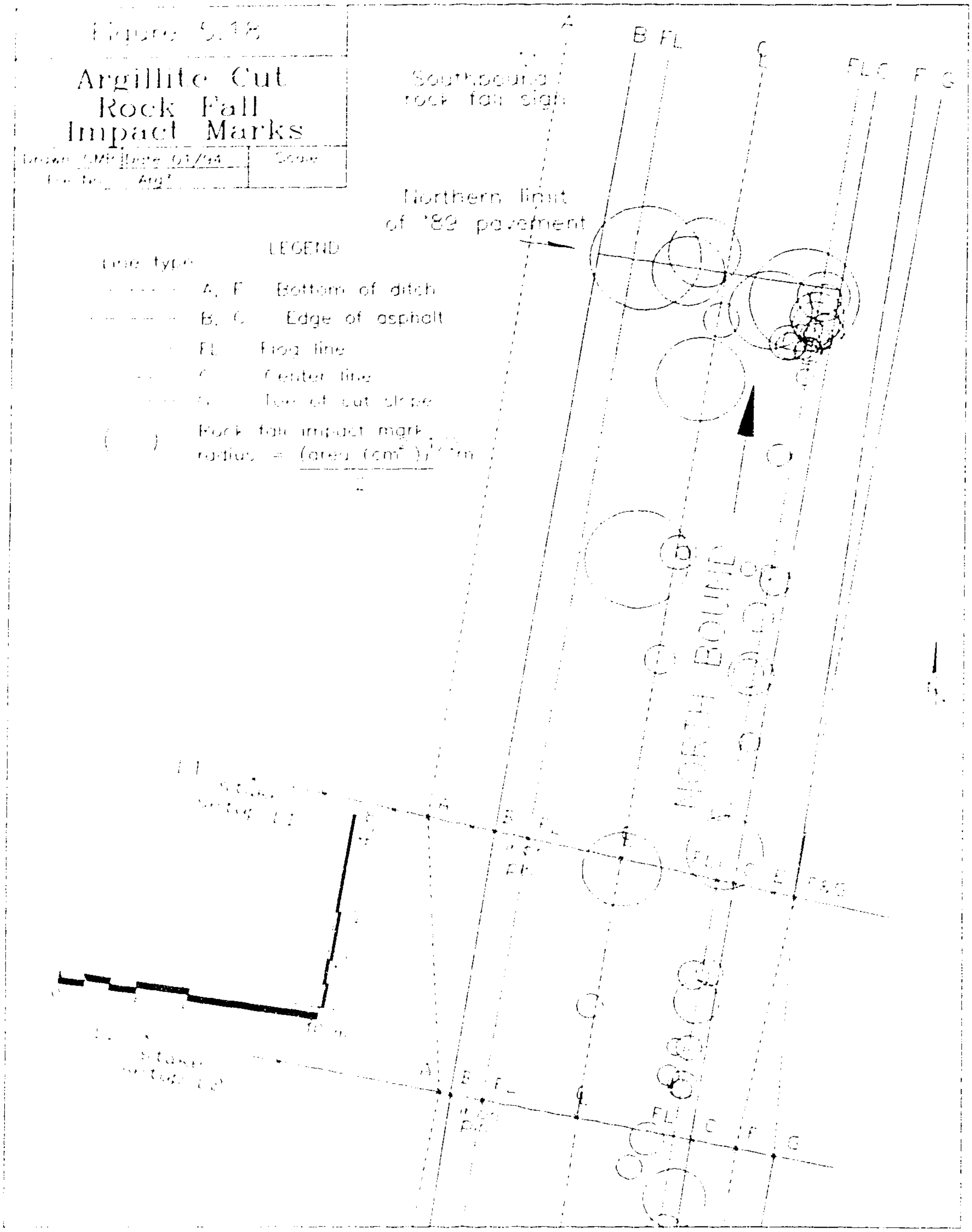


Figure 5.18 Mapping of the rock fall impact marks in the asphalt of the northern half of the Argillite Cut

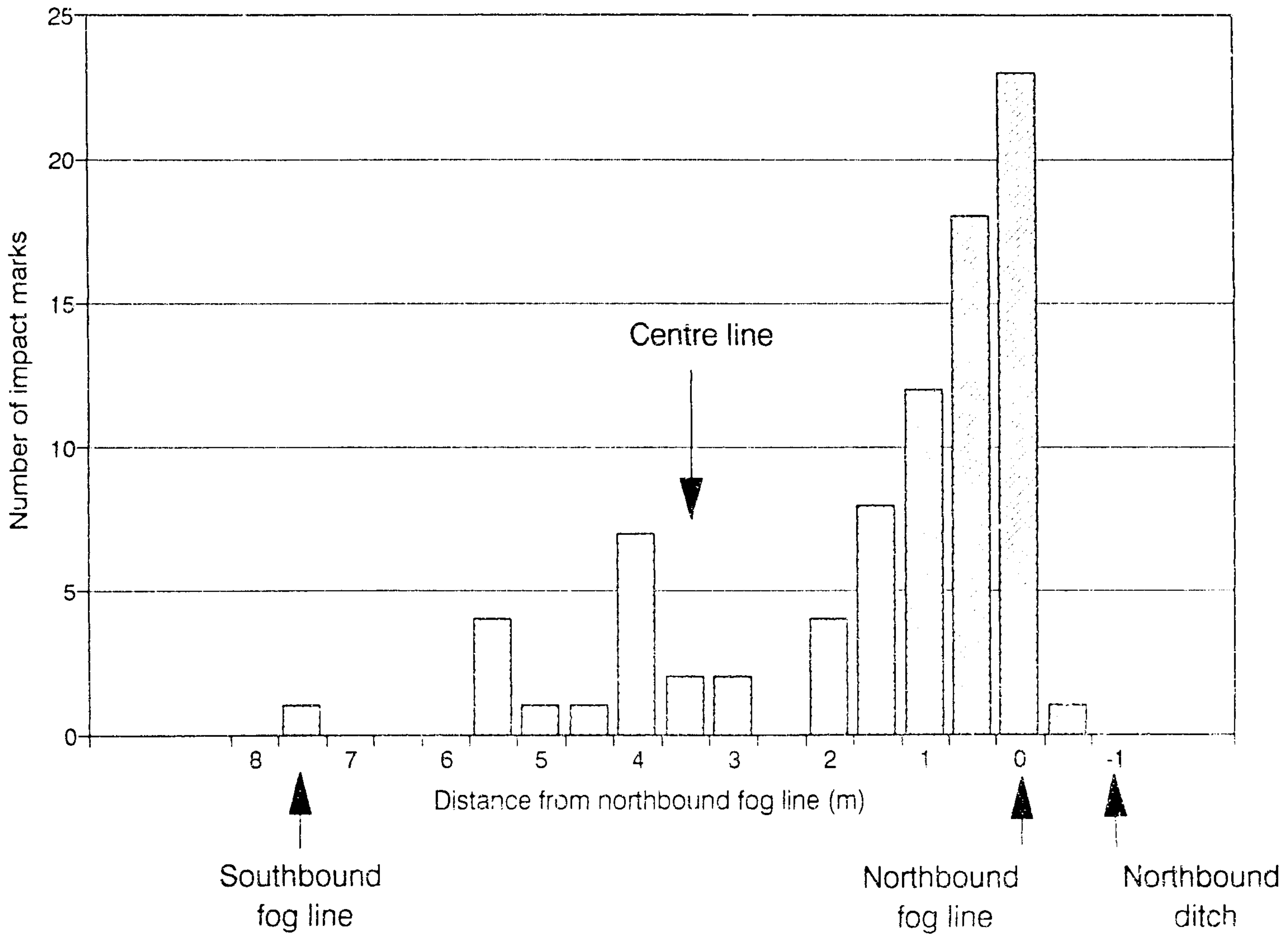


Figure 5.19 Distribution of rock fall impact marks at the Argillite Cut as a function of distance from the fog line

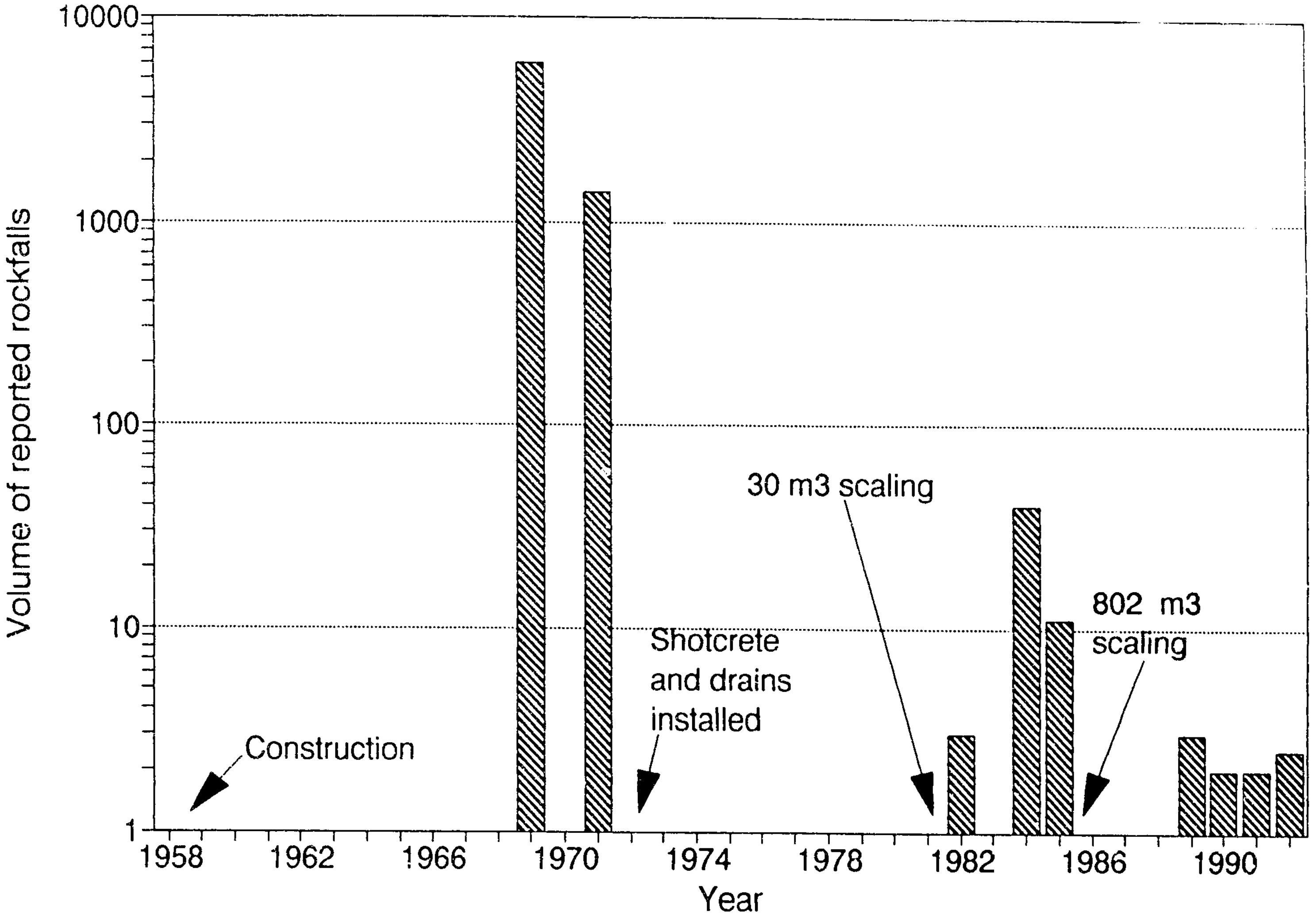


Figure 5.20 Volume of recorded rock falls at the Argillite Cut

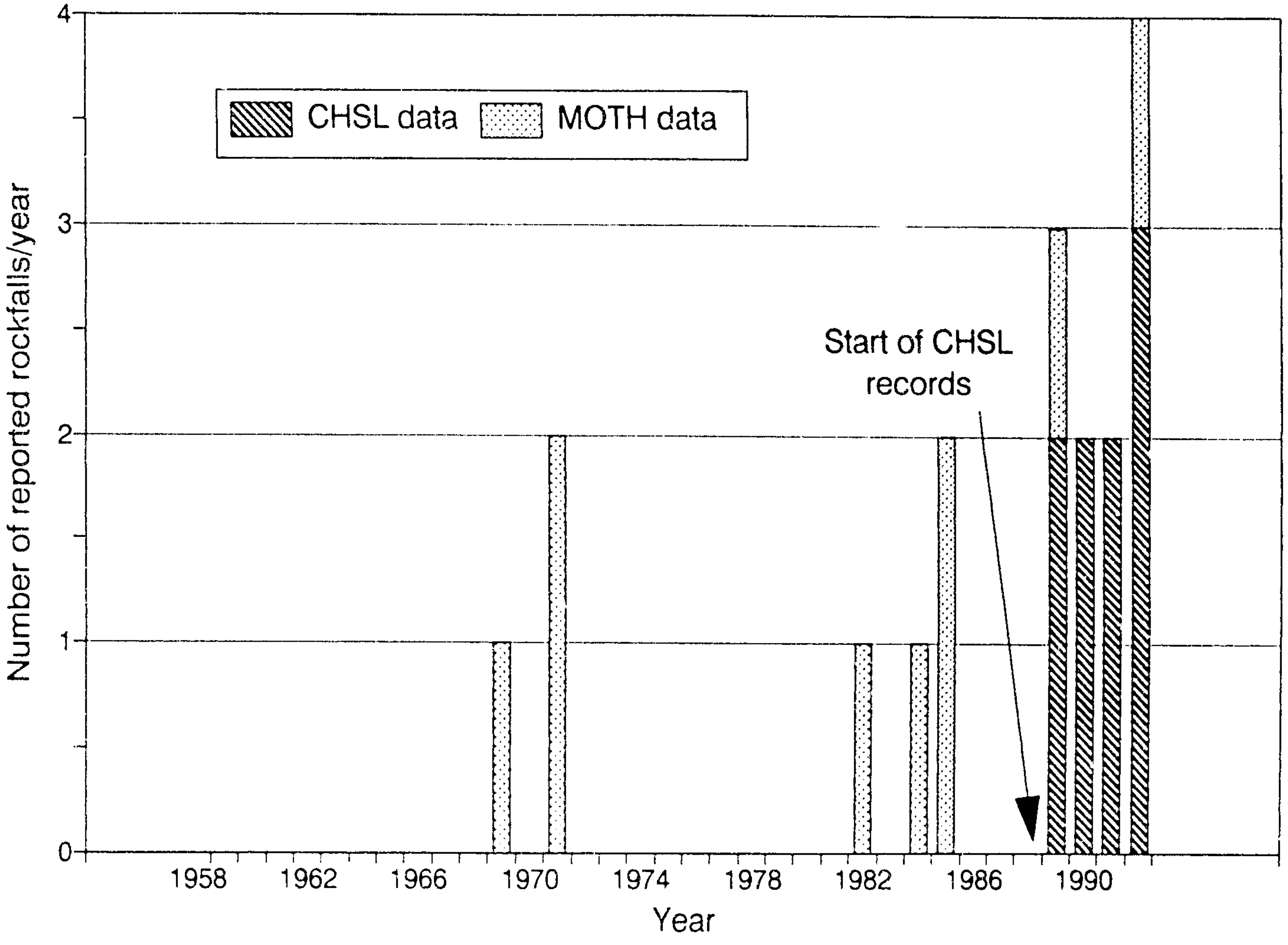


Figure 5.21 Number of recorded rock falls per year at the Argillite Cut

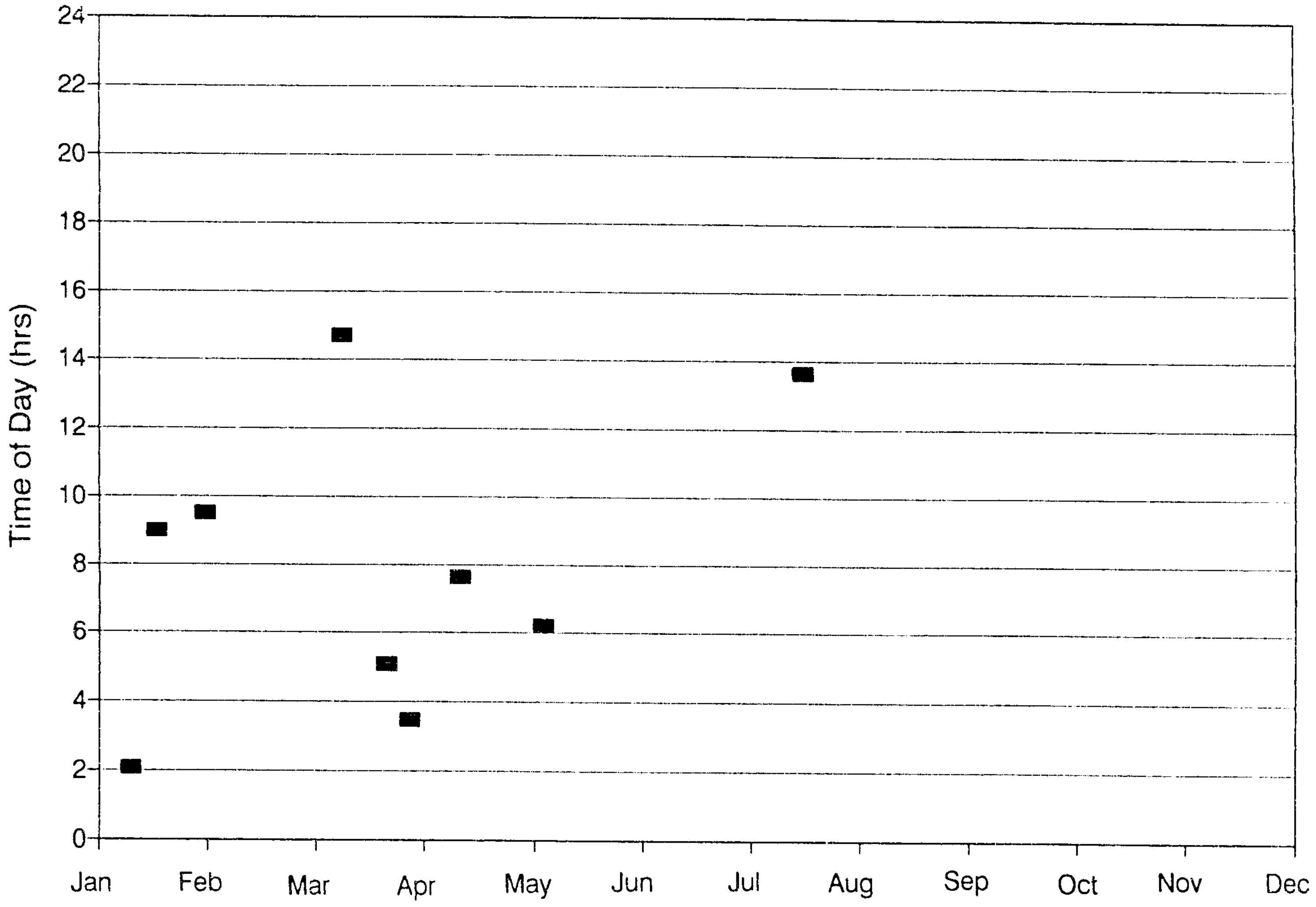


Figure 5.22 Diurnal distribution of recorded rock falls at the Argillite Cut

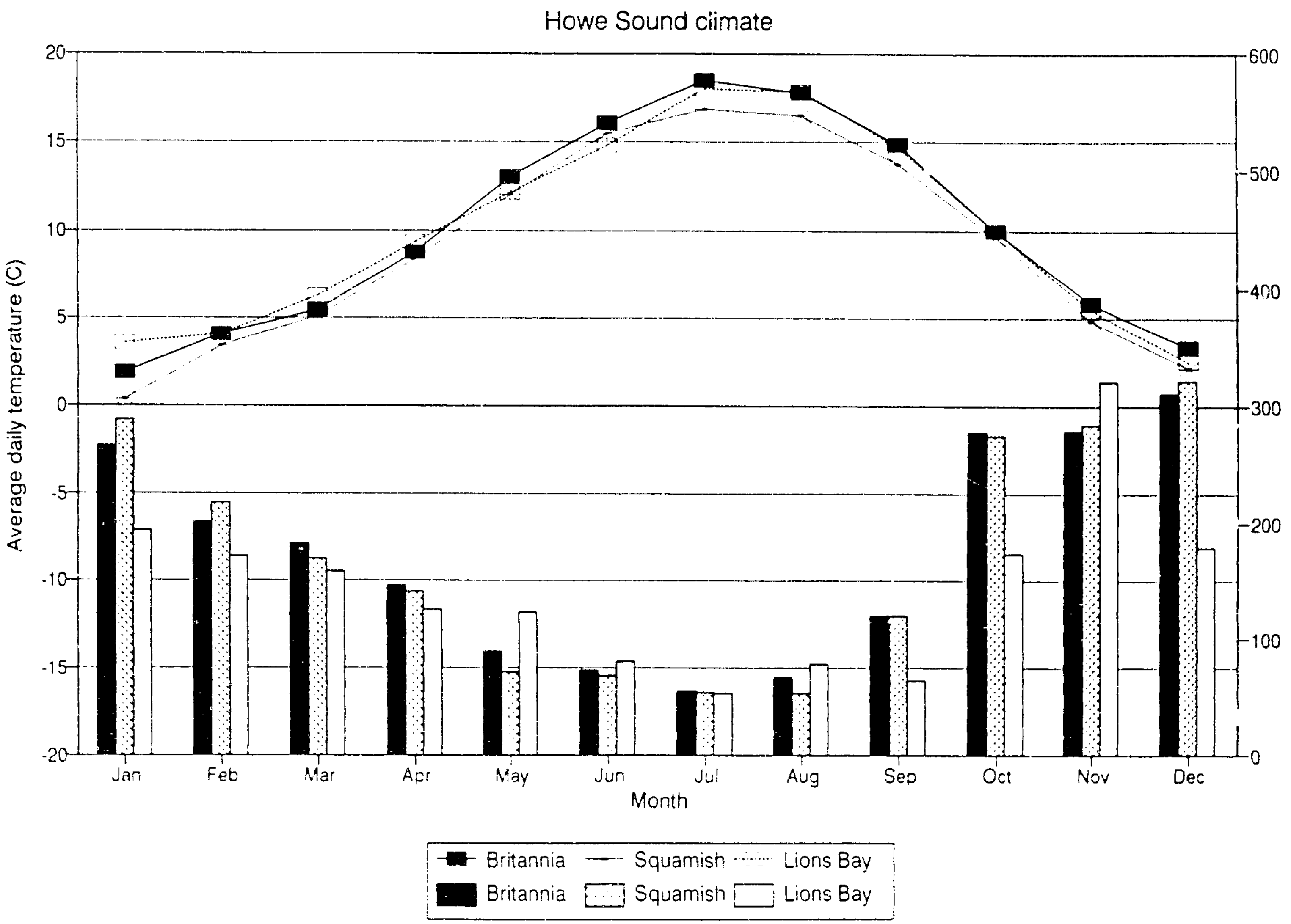


Figure 5.23 Climatological records for meteorologic stations near the Argillite Cut

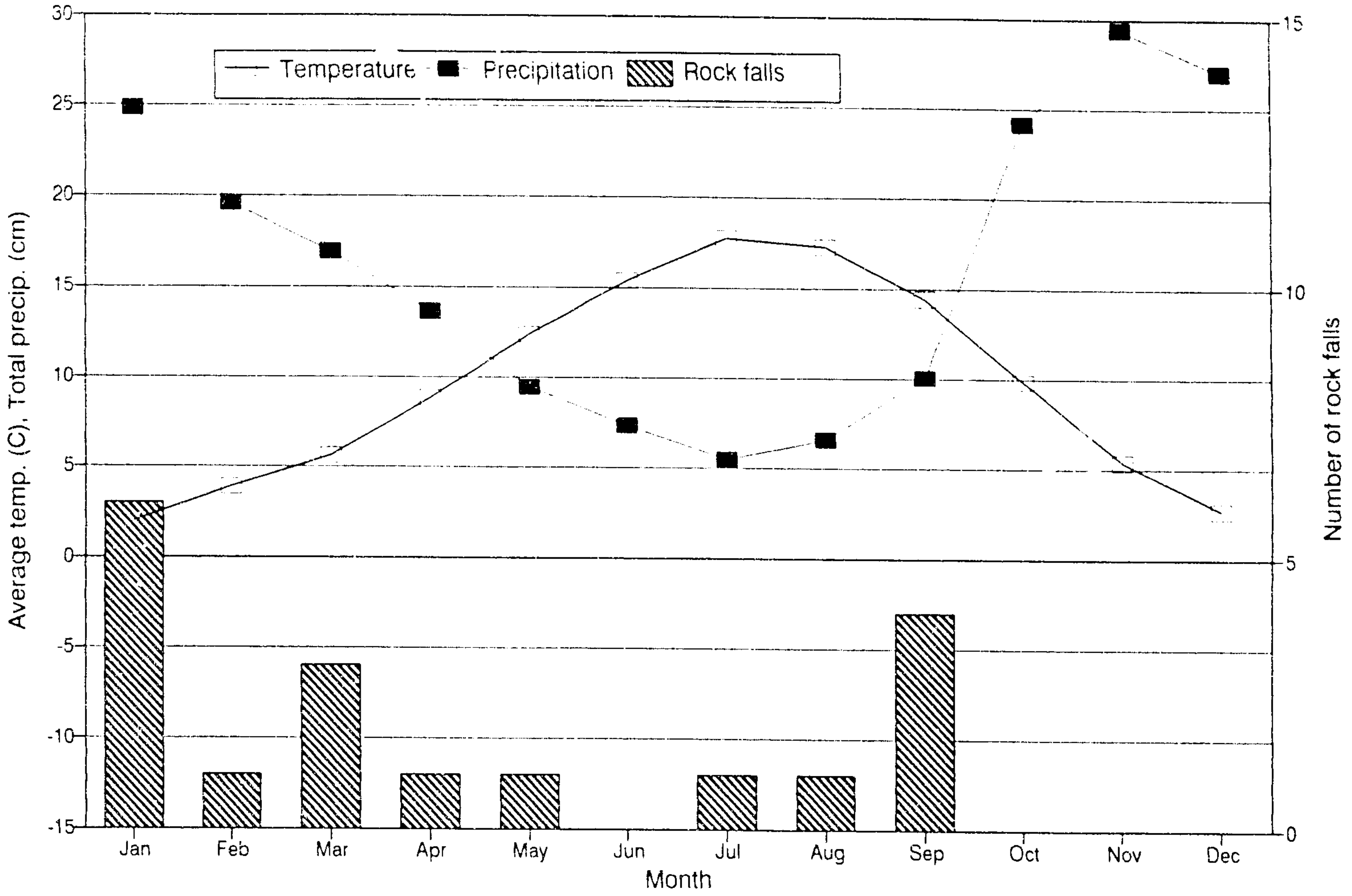


Figure 5.24 Lions Bay temperature and precipitation and the annual distribution of recorded rock fall activity at the Argillite Cut

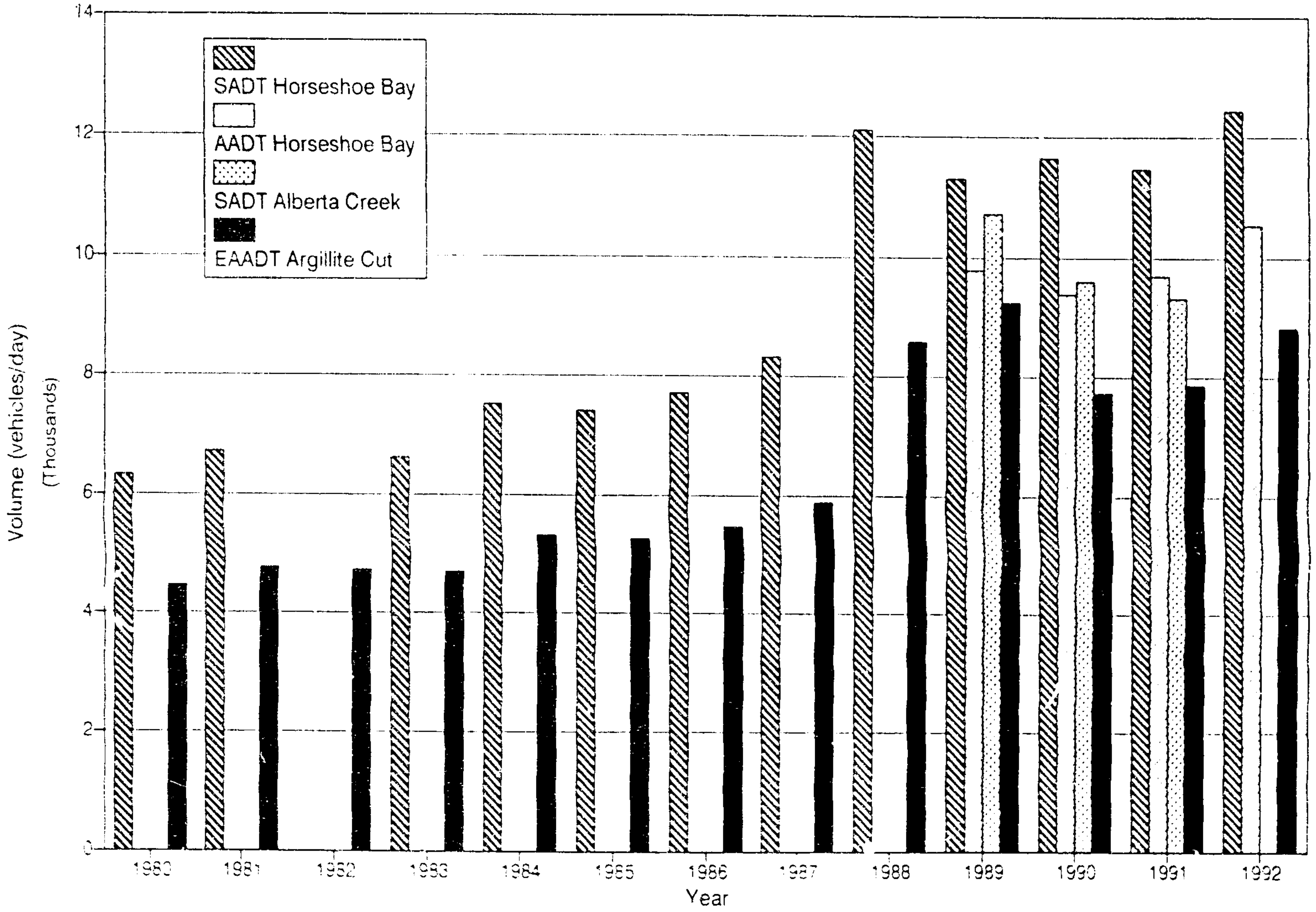


Figure 5.25 Estimated annual average daily traffic at the Argillite Cut and the recorded traffic data from Horseshoe Bay and Alberta Creek

6.0 Conclusions

6.1 General

This research follows a methodology for predicting the risks resulting from rock falls on highways, based on the CAN/CSA (1991) guidelines. The research then applies this methodology to the Argillite Cut on B.C. Highway 99 where the Just versus B.C. Case (Donald 1991) occurred. The development of this methodology demonstrates the first known application of the CAN/CSA (1991) guidelines to natural hazards.

Knowledge of the frequency of rock falls is essential to the accurate assessment of risk. Records of rock fall incidents are commonly incomplete. Sections 4.3.1.1 and 5.3.3.3 of this research demonstrate the use of mapping rock fall impact marks in the asphalt below active rock fall areas to supplement recorded rock fall information. This data is applicable to the calculation of rock fall risk because it provides an estimate of the rock fall frequency of only those falls that are a hazard to the roadway.

In order to assess whether the risk posed by rock fall is reasonable or unreasonable an acceptable level of risk should be established. Morgan (1991) suggested that the probability of death of an individual, PDI, accepted by society is less than $1 * 10^{-4}$ to $2 * 10^{-5}$. Fell (1993) identified that an annual PDI of not greater than $1 * 10^{-5}$ might be acceptable. Alternatively, Ale (1990) has suggested PDIs two to three orders of magnitude lower, between $1 * 10^{-6}$ and $1 * 10^{-8}$. It is to these levels of risk that the PDIs of the Argillite Cut, from the three types of rock fall vehicle interactions: stationary vehicle/falling rock, moving vehicle/falling rock, and moving vehicle/fallen rock are compared. Whitman (1984, p. 178) has suggested "accepted" and "marginally accepted" levels of the probability of N deaths, P(D) to the exposed population for engineering projects. The Canadian Dam Safety Association (CDSA) (Salmon 1994, personal communication) has proposed lower P(D)s for Dams than those of Whitman. Ale (1990) presented limits on P(D) lower than that of the CDSA for risks from hazardous materials. These differences may represent a trend towards lower acceptable risk levels or variations in acceptable risk level depending on the cause of the hazard. These risk levels are compared with the probability of death based on the population exposed to rock falls at the Argillite Cut.

The PDI from each type of rock fall vehicle interaction is compared with other voluntary and involuntary risks accepted by society in figure 6.1. Because the risk of a vehicle being hit by a falling rock and a vehicle hitting a fallen rock were analyzed independently, the total risk from rock falls to users of the highway is the sum of the two risks. To indicate the uncertainty in each of the PDIs the upper and lower bounds based on the total number of rock fall impact marks and the recorded rock falls respectively are included in figure 6.1. These risk values are based on the probabilities of death given impact, P(L:T), assumed in section 5.4 of 0.125 for rock fall on a stationary vehicle, 0.2 for rock fall on a moving vehicle, and 0.1 for a moving vehicle hitting a fallen rock. The upper and lower bound do not reflect the inherent uncertainty in the P(L:T). Figure 6.1 also contains the ranges of the involuntary risk level previously identified. It is evident that the risks from rock fall at the Argillite Cut are above the lower limit of involuntary levels Morgan (1991) has suggested. The risks are also above those presented by Ale (1990). It should be noted that the single use per year of the roadway is identified as being voluntary while the use of the roadway 500 times per year involuntary. This is to indicate that persons using the highway once per year commonly do so for pleasure and therefore voluntarily while commuters' use of the highway is an involuntary component of their daily activity. Assuming highways are designed and maintained considering the risks to the most frequent users efforts to reduce these risks may be appropriate at this site.

Figure 6.2 adapted from Whitman (1984), Salmon (1994, personal communication) and Ale (1990) indicates that the combined P(D) of death from rock fall / vehicle interactions in the Argillite Cut is above Whitman's marginally acceptable range, the CDSA's $10,000 per year criteria and within Ale's unacceptable range.

In addition to the Argillite Cut, there are several other rock fall prone areas along B.C. Highway 99. These include Porteau Bluffs where Holt (Smith J. 1994) was killed in 1991, Windy Point, Tunnel Point, Newman Creek and others. As a result, if B.C. Highway 99 between Vancouver and Squamish is considered a single engineering project the probability of N deaths may fall above Whitman's "marginally accepted" risk level. Similarly, when considering the entire length of the highway, the PDI using the highway 500 times per year may exceed the 1.0 * 10^{-4} level. The decision to assess the risk of the entire highway as a whole or each [illegible] individually is beyond the scope of this research. However, if the highway is considered a single project, it is appropriate that B.C. Ministry of Transportation and Highways (MOTH) inspect the highway for rock fall conditions and take measures to minimize rock fall events. The decision on how to distribute those efforts should be based on the risks of the different cuts and the use of relative rating systems such as the RHRS.

The risk of one or more deaths of the exposed population increases with increasing traffic volume. Figure 6.3 shows the increase in risk since the Just incident due to the almost doubling of the traffic flow on this highway. The combined return period for a death due to rock fall at the Argillite Cut at 1991 traffic levels is approximately 8 years. Risk analysis and the level of compensation paid to rock fall fatality victims can be used to assess the value of effort that should be expended to reduce rock fall risks. To achieve a net economic benefit, the annual expense of reducing the risk would have to be less than the product of the cost of compensating a victim and the difference of the original and lowered P(D). For example, based on the settlements awarded in the Just v. B.C. and Lewis v. B.C. cases of approximately $1 million each, and using the calculated 1992 return period of 8 years from figure 6.3, MOTH could economically justify the expenditure if the cost of halving the risk was less than $62,500 per year. MOTH (Sellig 1993, personal communication) records indicate that the 1987 scaling and bolting operations at the Argillite Cut cost $150,000, not including inspection and, as demonstrated by this case study has produced a calculated return period death rate of 8 years for the period following the remediation.

6.2 Legal precedent

Society has limited resources available to minimize natural hazards and, as a result, it must accept some level of risk. Since rock fall activity is foreseeable, some level of activity should be considered acceptable. The Supreme Court of Canada (Cory J. and Sopinka J. 1989) suggested the if MOTH "... had in all circumstances met the standard of care that should reasonably be imposed upon it with regard to the frequency and manner of inspection of the rock cut and to the cutting and sealing operations carried out upon it" (p. 1246) MOTH would not be liable for losses suffered by victims of rock falls on roadways. The level of inspection and remediation required to meet the requisite standard of care should be related to the risks involved and should result in an acceptable level of rock fall activity. Therefore comprehensive records of rock falls and the efforts made to assure an acceptable level of risk could provide a defense that adequate engineering had been applied.

The Supreme Court of B.C. (Donald J. 1991) decided that MOTH had not met the requisite standard of care deemed appropriate based on expert testimony in the Just Case. The criteria used to arrive at this decision did not include the benefit of a risk analysis. If the B.C. Supreme Court had been aware of the level of risk that Just was exposed to by rock falls it may have come to a different conclusion. The judiciary should have access to a risk analysis to consider the risk level it is imposing when arriving at a decision.

When determining negligence with respect to rock fall prevention, the test applied by the judiciary might consider whether the level of inspection and expenditure of resources to reduce the risk to highway users were sufficient to achieve an acceptable level of risk. The identification and remediation of specific rocks that may fall may only be warranted if the road cut exhibits a frequency of rock fall activity or potential for rock fall that poses an unacceptable risk to the exposed population. MOTH has a obligation to keep records of rock fall activity, inspections and remediation efforts to determine what risks exist.

At the time of the Just fatality, four rock falls had been recorded during the twenty four year history of the Argillite Cut. The records also indicate that the considerable remediation efforts had been expended on the Argillite Cut following two falls in 1972. Given the recorded rock fall frequency and the potential for rock fall activity of the Argillite Cut, the courts might have considered the level of inspection and remediation sufficient to have achieved an acceptable level of risk. Using the risk analysis developed in this thesis and the information available at the time of the combined P(D) and the PDI for a commuter are $5.9 * 10^{-3}$ and $4.7 * 10^{-6}$ respectively. This P(D) is lower than that Whitman's accepted level which can be considered the state of practice at the time of Just. The PDI is unacceptable according to Ale (1991) but is in Morgan's (1991) acceptable range. Therefore the decision of the Supreme Court of B.C. (Donald J. 1991) may have placed an unreasonable burden on MOTH because it requires MOTH to provide a lower level of risk than was expected by society at the time of the Just incident. When the B.C. Supreme Court decided in favor of Just, it effectively set the range of acceptable risk for future cases.

It is evident from figures 6.1 and 6.2 that the probability of the circumstances of the Just Case occurring are the lowest of the three rock vehicle interactions. MOTH should not be expected to maintain highways such that persons can occupy a road cut on an ongoing basis. Alternatively, they should allow for periodic traffic delays that may force vehicles to stop in a cut. If delays are frequent events MOTH should consider means of avoiding vehicles stopping in hazardous areas. Alternatively, if a half hour delay occurs once or twice a year this analysis demonstrates that the risk of death by rock fall while stopped in the Argillite Cut is acceptably low. Even if long delays were expected, this half hour period should allow highways personnel sufficient time to reroute or direct delayed vehicles away from rock fall prone areas. The use of rock fall signs stating "Rockfall Hazard Area No stopping for 400 m" at the Argillite Cut is an effort to produce this result. In cases where traffic is delayed by MOTH it should not be stopped in a hazardous cut.

In conclusion, due to the quality of the rock fall activity records, the uncertainty in P(L:T), and depending on the expression of the risk, and the level of risk considered acceptable, this research indicates that it is uncertain whether MOTH inspected and maintained the Argillite Cut at an acceptable level of risk prior to the Just Case. More comprehensive recording of rock fall activity, the refinement of the P(L:T) term and the application of the methodology developed in this research could be used to determine the risk of a cut or length of highway.

6.3 Weather

A review of the recorded rock fall incidents at the Argillite Cut revealed that approximately half could be correlated to recorded climatic conditions that may have triggered a fall. Therefore the frequency of rock falls can be expected to be higher during freeze-thaw and precipitation events. Alternatively, half the recorded rock fall events occurred without an identifiable recorded climatic trigger and therefore pose a hazard at any time. As a result a reduction in the risk could be achieved by closing the highway during severe climatic conditions. Severe climatic conditions may make B.C. Highway 99 impassable due to snow as in the Just Case or debris flows (Morgan et al. 1992, Jackson et al. 1985).

6.4 Remediation

It has been demonstrated that the risk of death due to fallen rock is greater than that of falling rock in the Argillite Cut. Therefore it is appropriate that the agency responsible for highway safety address any efforts to minimizing the risk of this hazard first. In addition, to minimizing rock fall frequency and magnitude, other methods of reducing hazards from fallen rock include reduced speed through rock fall zones, frequent highway patrols to remove fallen rock, emergency telephones on highways to report rock falls and accidents, traffic controls and warning systems that reduce the number of vehicles in rock fall zones during hazardous climatic conditions, deeper and wider ditches, and wider roads to allow drivers more room to avoid fallen rocks. During hazardous climatic conditions, alternate transportation could be utilized. For example, during the October 1990 B.C. Highway 99 road closure ferry service was provided by the British Columbia Ferry Corporation operating between Horseshoe Bay and Darrel Bay (British Columbia Ferry Corporation Annual Report 1991). Several of these latter methods may be cost effective in comparison to the expenditure required to reduce the number of rock falls.

6.5 RHRS correlation to risk

The simultaneous application of the RHRS and the risk assessment of a rock fall cut allows the correlation of the two methodologies. Therefore it is reasonable to assume that the risk of a highway cut with an RHRS score of 490 would have a P(D) and a PDI of the same magnitude as the Argillite Cut. At present no published RHRS values are available to compare with this score.

7.0 Further Work

Several areas of this research related to rock fall on highways require further investigation. One area of research is rock vehicle interaction. This includes analysis of the probability of death given rock fall impact on a vehicle, and the effect of rock fall size on the probability of death for the three cases. A second area of research is the rock asphalt interaction including the relationship between rock impact marks and the size of falling rocks. The coefficient of restitution of rock and asphalt should also be determined for use in numerical modeling of rock fall trajectory. A third area of research is the quantification of the traffic on particular highways. This includes the average length of vehicles, and vehicle occupancy of traffic passing through specific rock fall areas. In addition, investigation of the distribution of rock fall zones and the location of areas where traffic can be safely stopped to avoid exposure to rock fall hazards is required. A fourth is the direct quantification of the rock fall size and frequency relationship at the Argillite Cut and other hazardous cuts above highways. A fifth is the cause and trigger of rock falls.

Calculation of the rock fall risks of the entire length of B.C. Highway 99 is also of interest as are the rock fall risks on all roads in the province. This information would allow MOTH to determine resources they should expend on minimizing rock falls on a regional and provincial basis.

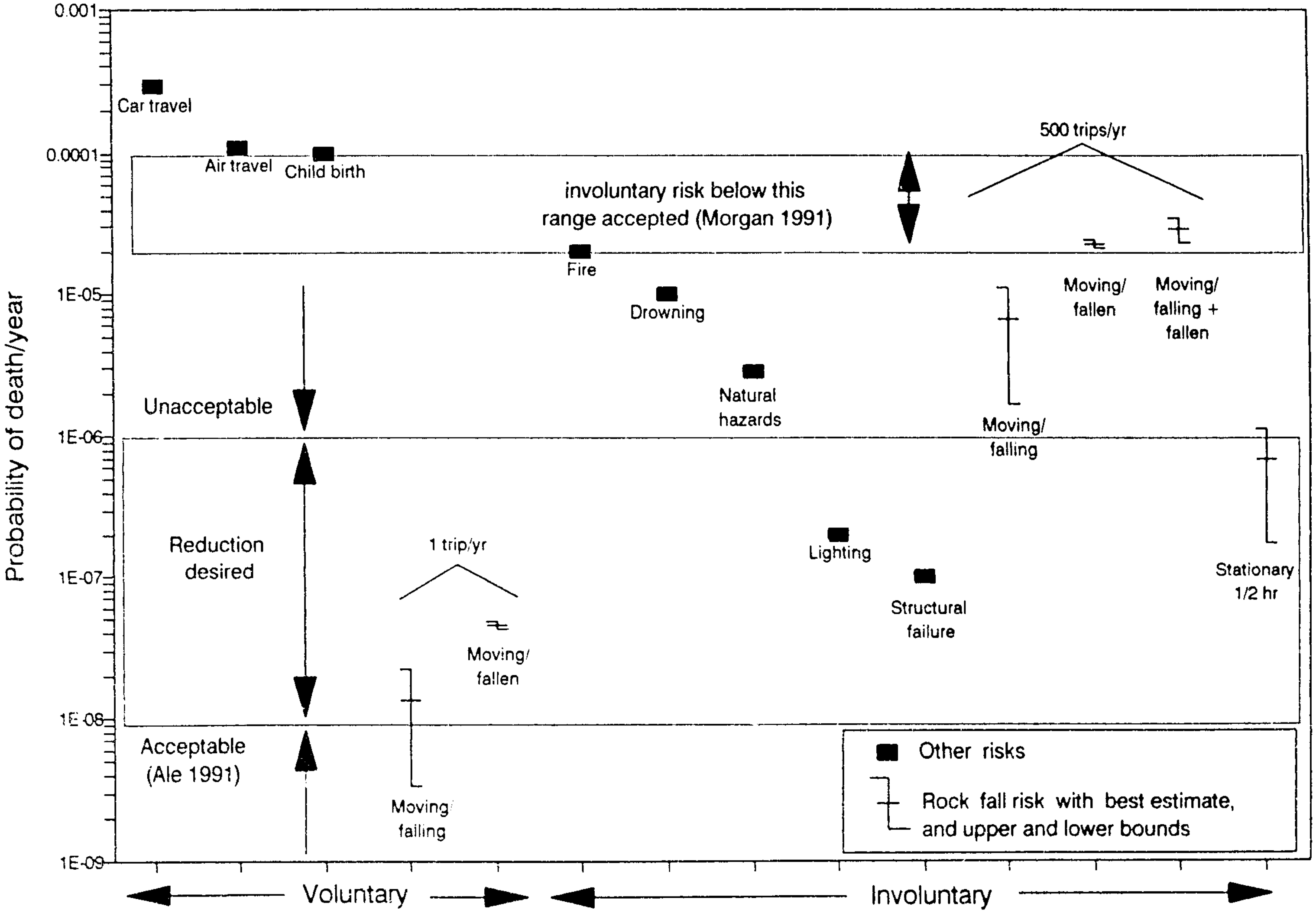


Figure 6.1 Probability of death of an individual in the Argillite Cut compared to the risk of involuntary and voluntary activities

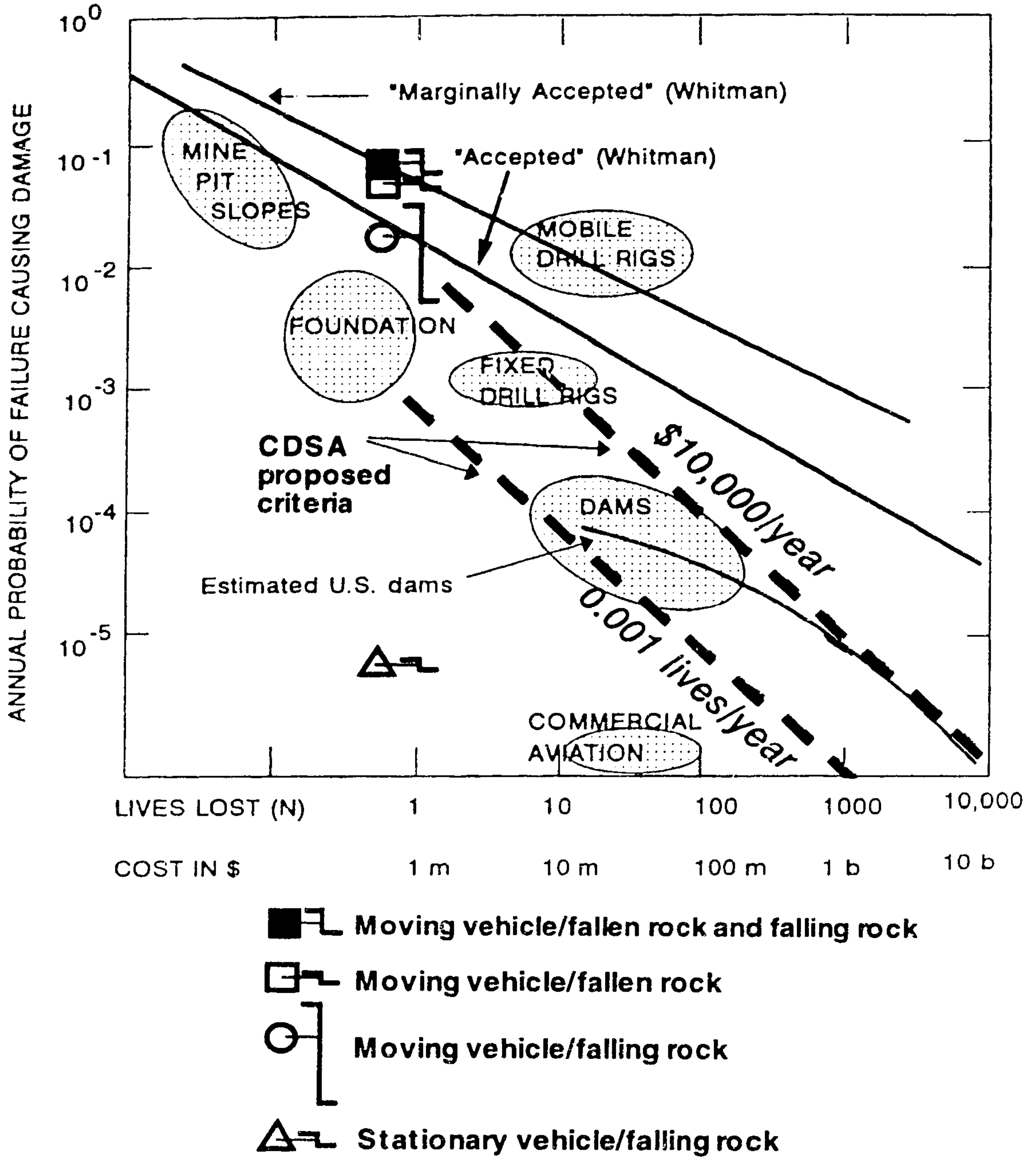


Figure 6.2 Risk of death, P(D) with upper and lower bounds for rock fall at the Argillite Cut compared to that of selected engineering projects

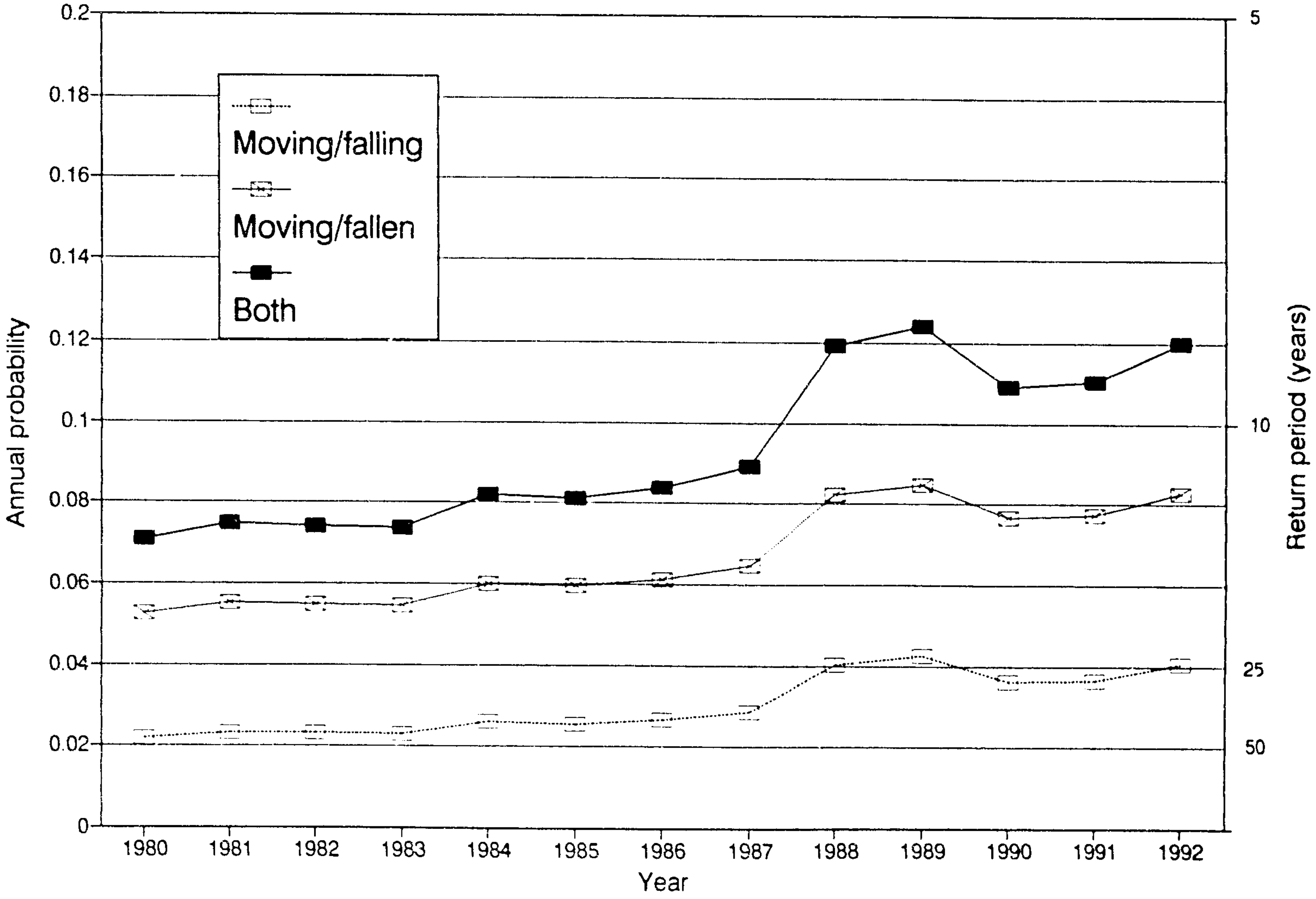


Figure 6.3 Probability of death at the Argillite Cut for the annual population exposed from 1980 to 1992

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Appendix A: Rock fall impact mark mapping data

Appendix A: Rock fall impact mark mapping

No.	Distance from north bound rock fall sign x (m)	Distance left of fog line y (m)	x' (cm)	y' (cm)	z' (cm)	Area x'y' (cm^2)	Volume 1/3x'y'z' (cm^3)	Comments
	0							
	4	-0.6	7	11	1	77	25.7	
	31-41.6	Scratches and marks outside fog line						
	41	0.3	8	6	1	48	16.0	
	44.1	0.3	6	7	1	42	14.0	
	44.1	-0.1	7	4	1	28	9.3	
	44.6	Start of new pavement						
1	50.3	-0.6	16	22	6	352	704.0	may be defect
	72	Start of shot crete						
	97.6	End of southwest no posts						
	127.5	Line X-3						
2	130.2	1	5	3	1	15	5.0	
3	131.0	3.5	3	3	1	9	3.0	
4	131.3	0.4	6	3	1	18	6.0	
5	132.2	1	25	25	2.5	625	520.8	Two photo's
6	133.0	5.2	5	3	2	15	10.0	
7	133.5	1	2	2	1	4	1.3	
8	133.8	3	3	2	1	6	2.0	
9	135.6	1.5	3	2	1	6	2.0	
10	135.7	1.5	3	2	1	6	2.0	
11	137.6	0.6	5	3	2	15	10.0	
12	139.1	0.2	9	14	2	126	84.0	
13	141.0	2	4	6	1	24	8.0	
14	141.2	0.6	7	12	2	84	56.0	
15	141.8	7.5	5	4	2	20	13.3	
16	142.0	0	5	5	1	25	8.3	
17	145.5	0.5	10	10	1	100	33.3	
18	145.6	0.6	8	8	1	64	21.3	
19	150.5	5.2	5	8	1	40	13.3	
20	151.9	-0.1	8	10	0.5	80	13.3	
	154.7	Sign "Deeks Lake Trail 500 m" moveable						
21	158.9	-0.2	4	10	0.5	40	6.7	
22	168.3	1.5	3	3	1	9	3.0	

Appendix A: Rock fall impact mark mapping

No.	Distance from north bound rock fall sign x (m)	Distance left of fog line y (m)	x' (cm)	y' (cm)	z' (cm)	Area x'y' (cm^2)	Volume 1/3x'y'z' (cm^3)	Comments
23	169.2	-0.1	3	8	1	24	8.0	
24	177.6	-0.2	10	7	2	70	46.7	
	127.5	Tuff						
25	186.8	3	3	3	1	9	3.0	
26	189.7	2	6	3	1	18	6.0	
	127.5	Loader teeth scratches in edge of asphalt, picture #9.						
27	199.0	5.2	10	5	2	50	33.3	
28	199.1	4.2	12	12	2	144	96.0	South lane +.5
	201.9	Creek Centreline						
29	202.5	5	10	10	2	100	66.7	South lane
30	202.6	0.4	5	4	1	20	6.7	
31	205.3	2	3	3	1	9	3.0	
32	206.8	1.5	5	5	1	25	8.3	
	127.5	Loader scratches						
33	210.2	1.5	3	2	1	6	2.0	
	212.4	2.2	1	5	1	5	1.7	Defect in asphalt
34	213.6	1.3	2	15	1	30	10.0	
35	214.5	0.8	5	7	1	35	11.7	
36	219.8	0.4	7	15	1	105	35.0	
37	219.9	0.4	4	4	1	16	5.3	
38	222.0	-0.3	10	10	2	100	66.7	
	223.0	1	20	2	2	40	26.7	Traffic scratch
	223.1	Tuff and argillite interbedded to the north						
39	225.2	3.6	15	20	3	300	300.0	10 cm east of centerline
	236.7	Argillite with minor tuff to north						
40	241.9	-0.2	5	10	0.5	50	8.3	
41	248.9	-0.4	10	15	1	150	50.0	
42	254.0	1.5	5	5	1	25	8.3	
	260.2	1	15	3	1	45	15.0	Looks man made
	261.5	Line X-2						
	261.5	Line X-2						
43	271.3	0	4	4	1	16	5.3	
44	272.2	0	8	4	1	32	10.7	

Appendix A: Rock fall impact mark mapping

No.	Distance from north bound rock fall sign x (m)	Distance left of fog line y (m)	x' (cm)	y' (cm)	z' (cm)	Area x'y' (cm^2)	Volume 1/3x'y'z' (cm^3)	Comments
45	273.7	0.6	6	3	1	18	6.0	
46	279.6	0.5	4	3	1	12	4.0	
47	279.9	0	5	5	1	25	8.3	
48	285.4	4	5	5	1	25	8.3	+0.3 from centreline
49	289.4	0	10	8	1	80	26.7	
50	294.8	0.3	6	6	1	36	12.0	
51	295.8	-0.3	4	7	1	28	9.3	
	306.0	to north the east cut is striated argillite, west side is fill						
52	314.0	3.7	15	15	1	225	75.0	Centreline
	314.8	Line X-1						
	314.8	Line X-1						
53	320.5	-0.1	15	15	2	225	150.0	Round
	324.0	end of argillite Tuff to north						
54	328.3	0.4	3	3	1	9	3.0	
	342.0	end of northwest no posts						
55	343.4	-0.3	4	4	0.5	16	2.7	
56	357.4	0.1	8	10	1	80	26.7	
57	357.5	0.2	5	7	1	35	11.7	
58	357.6	3.7	6	6	1	36	12.0	On centerline
59	369.1	0.2	6	6	0.5	36	6.0	Light dent, not sharp
60	376.9	-0.2	7	5	1	35	11.7	
61	377.2	5.2	20	20	2	400	266.7	
62	378.5	0.1	3	3	1	9	3.0	
63	378.5	0.9	3	3	1	9	3.0	
64	379.7	3.7	7	7	0.5	49	8.2	
65	379.8	3.5	4	2	0.5	8	1.3	-0.2 m from centreline
	402.5	0.5	10	2	1	20	6.7	pavement defect
	415.2	start of 2-5 cm dia fragments of rock on road inside of the fog line. Photo						
66	415.6	4	15	20	2	300	200.0	+.3 from centreline
67	419.2	0.05	3	4	1	12	4.0	
	419.7	end of 4-5 fragments /m on road						
68	424.6	0.1	6	5	1	30	10.0	
69	425.0	0.1	5	5	1	25	8.3	

Appendix A: Rock fall impact mark mapping

No.	Distance from north bound rock fall sign x (m)	Distance left of fog line y (m)	x' (cm)	y' (cm)	z' (cm)	Area x'y' (cm^2)	Volume 1/3x'y'z' (cm^3)	Comments
70	425.1	0.8	6	5	1	30	10.0	
71	425.7	0.9	5	10	1	50	16.7	
72	426.3	0.4	10	5	41	50	683.3	
73	427.9	1.1	5	10	1	50	16.7	
74	427.8	-0.1	4	10	1	40	13.3	
75	428.0	-0.1	5	5	1	25	8.3	
76	428.2	3.6	5	10	0.5	50	8.3	-.1 from centreline
77	429.1	-0.4	7	7	1	49	16.3	
78	429.1	0.2	5	5	1	25	8.3	
79	430.4	0	16	5	1	80	26.7	
80	431.7	0	15	7	1	105	35.0	
81	431.8	1.8	17	15	3	255	255.0	
82	434.8	0.6	22	20	4.5	440	660.0	
83	435.7	-0.2	6	6	0.5	36	6.0	
84	436.1	-0.1	10	10	0.5	100	16.7	
	437.1	5.2	20	10	4	200	266.7	flaw in asphalt?
	437.9	End of new pavement						
		4-5 marks/m average 5,5,1 in old pavement with scratch marks						
	438.4	6.9	30	15	3	450		Scratch in old asphalt
	441.3	4.7	20	10	2	200		+1.0 from centreline
	454.3	End of North east no post						
	470.9	20 km marker						
	476.2	N.W rock fall sign			max	625.00	704.00	
					min	4.00	1.33	

Length of new pavement (m)	393		
Rock fall sign spacing (m)	476	scaled	per/year
Total rock marks	84	102	21.4
Number outside fog line	60	73	15.3
Number on or inside fog line	24	29	6.1
Number in south lane	9	11	2.3
Number in north lane	51	62	13.0

Appendix B: Meteorologic records for recorded rock falls

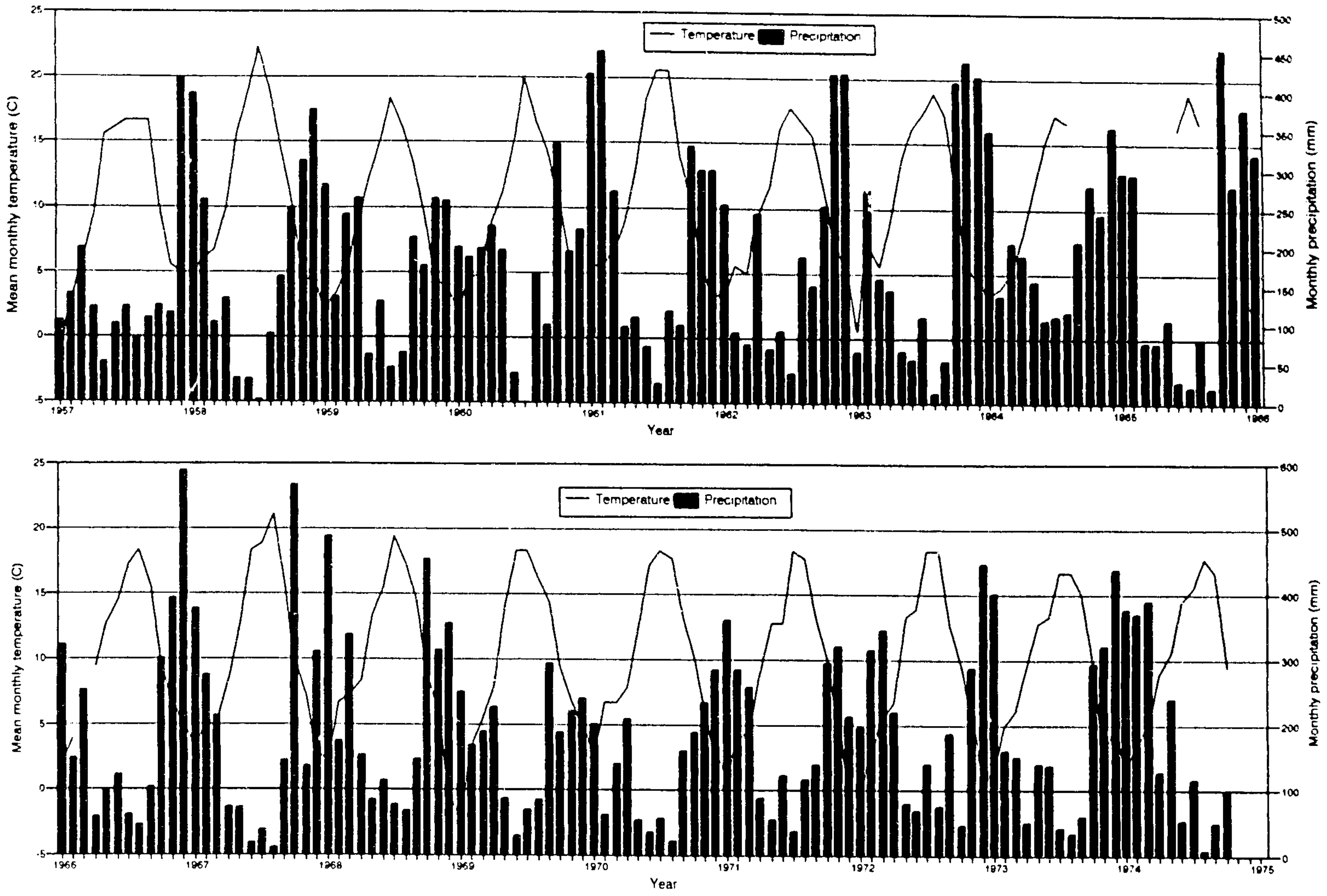

Figure B1 Britannia Beach meteorologic data 1957 - 1974

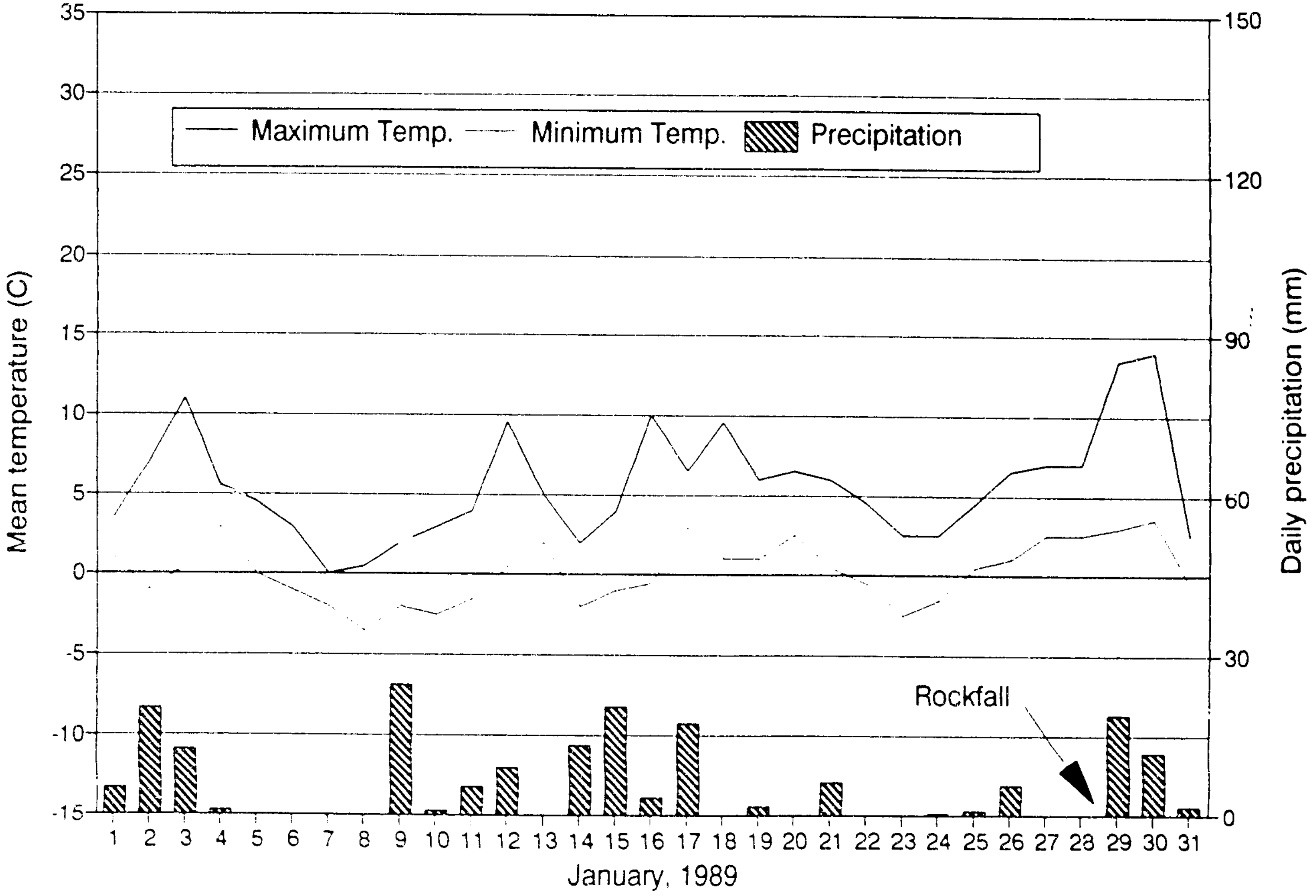

Figure B2 Lions Bay meterologic data January, 1989

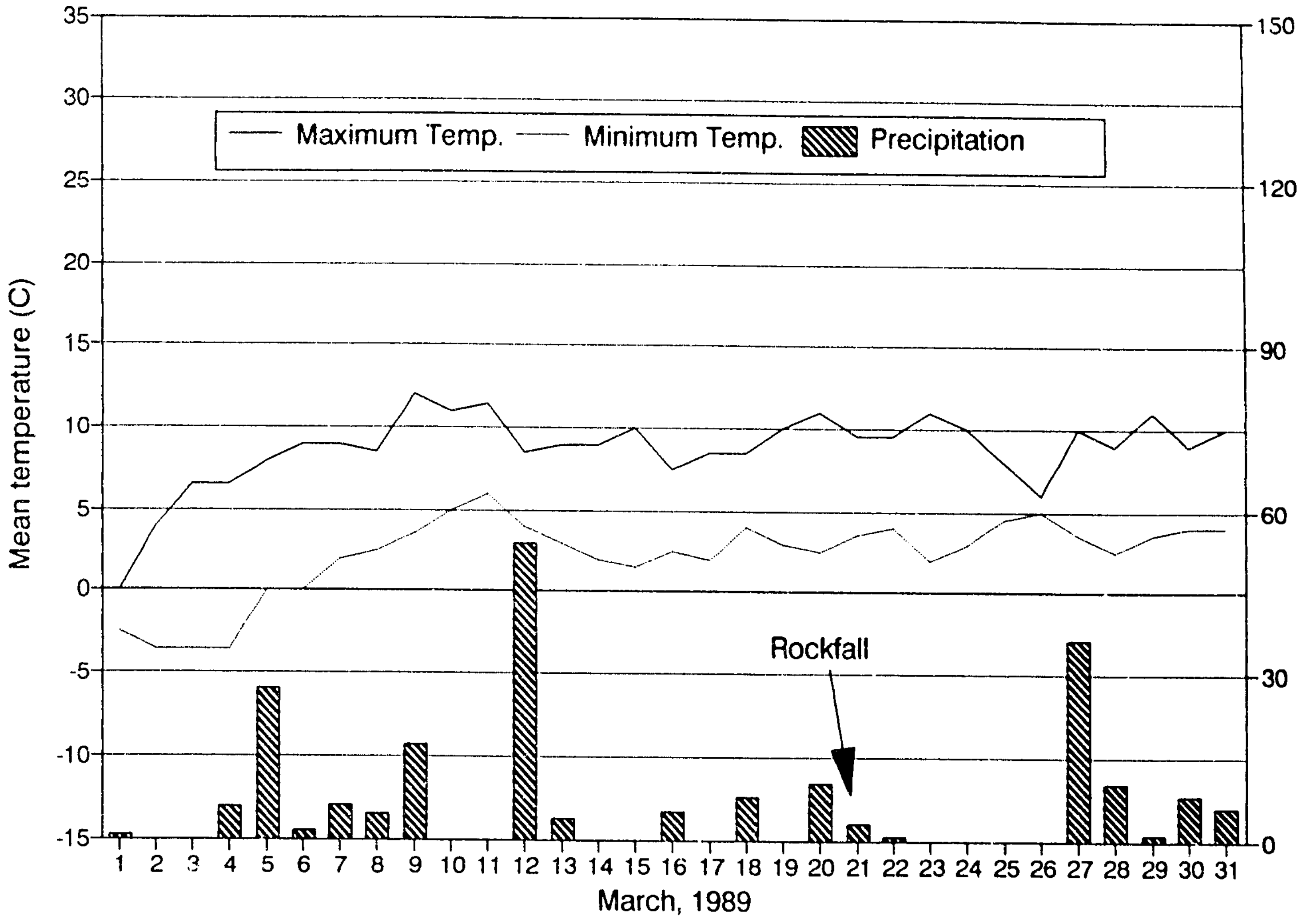

Figure B3 Lions Bay meteorologic data March, 1989

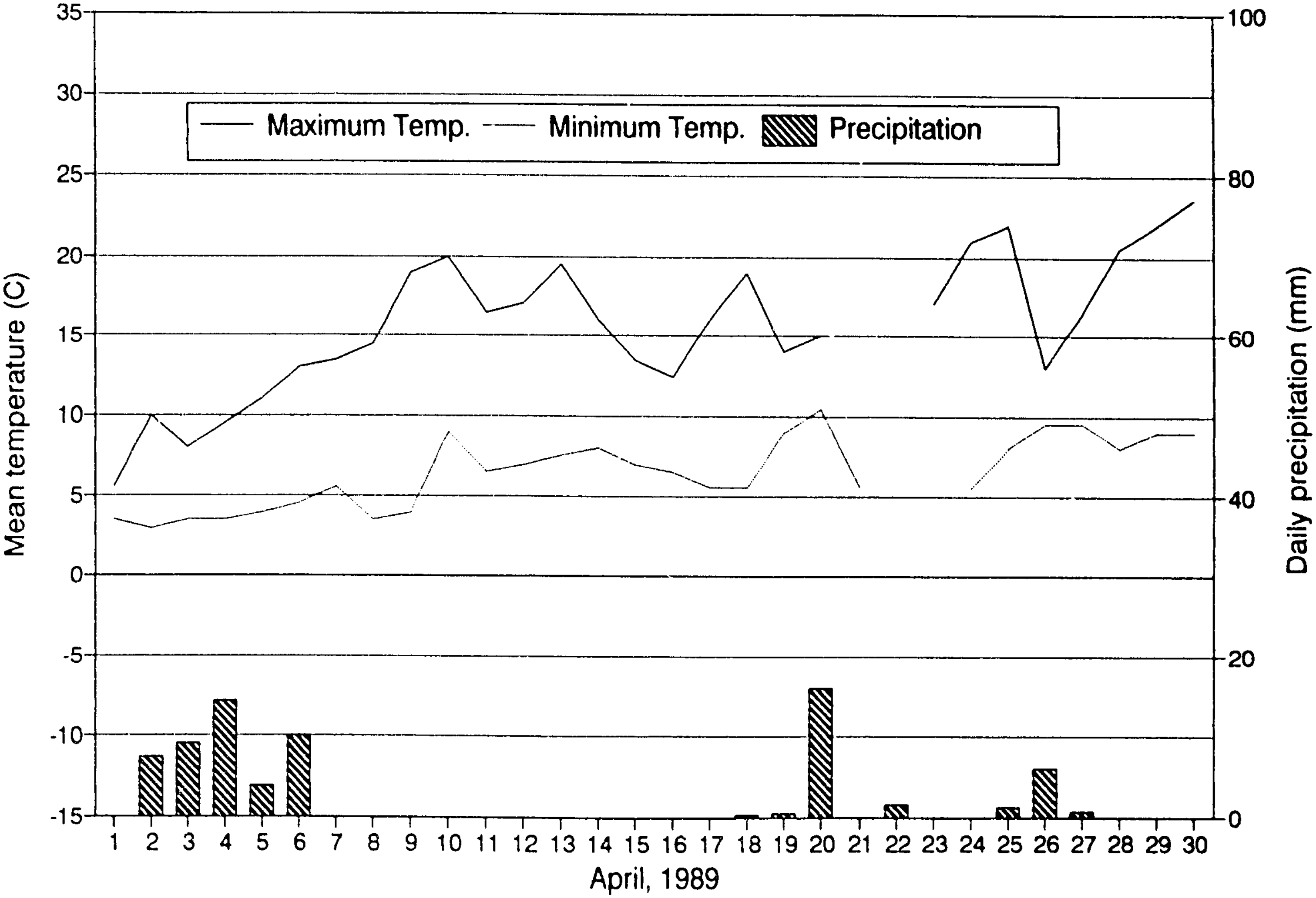

Figure B4 Lions Bay meteorologic data April. 1989

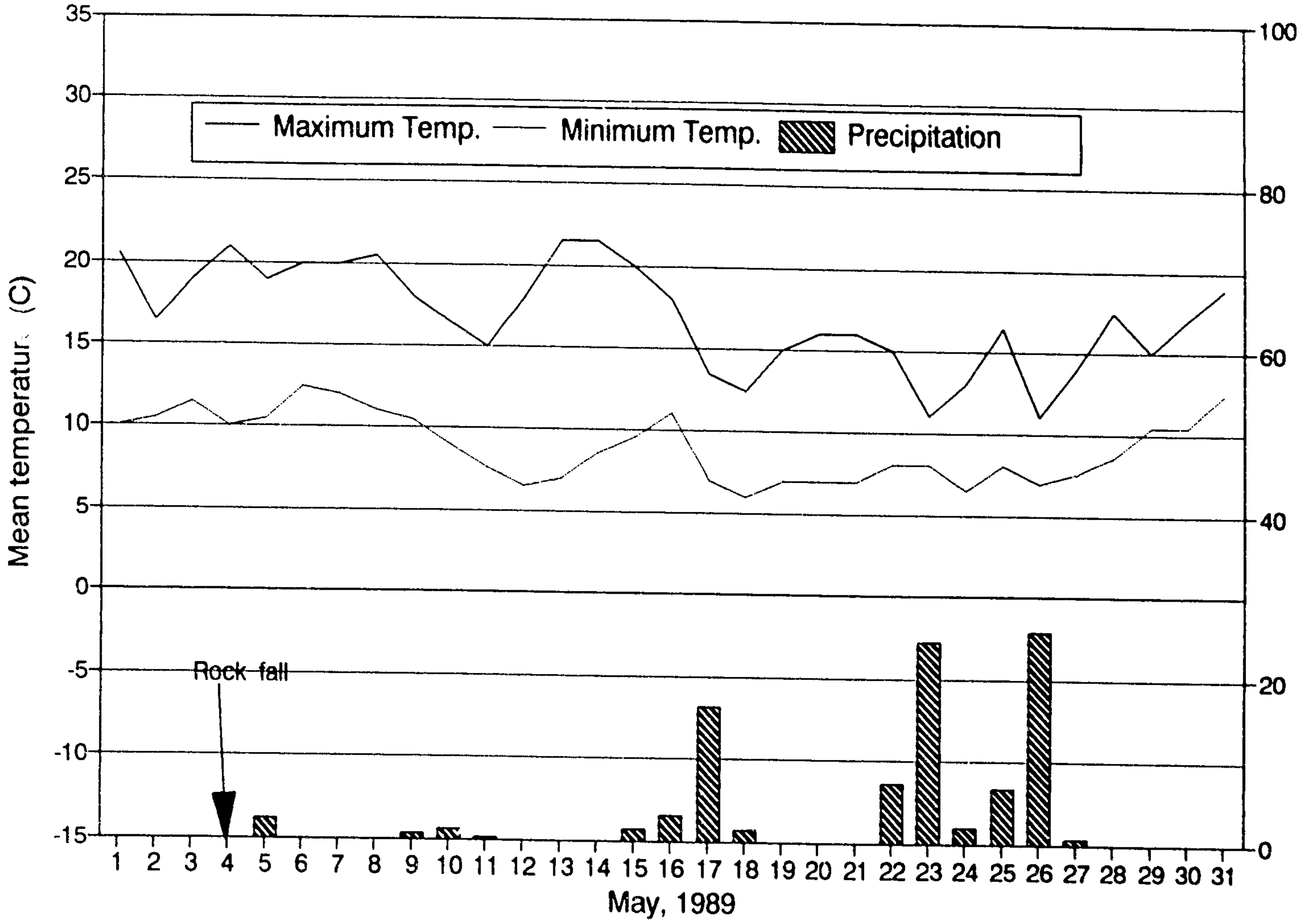

Figure B5 Lions Bay meteorologic data May, 1989

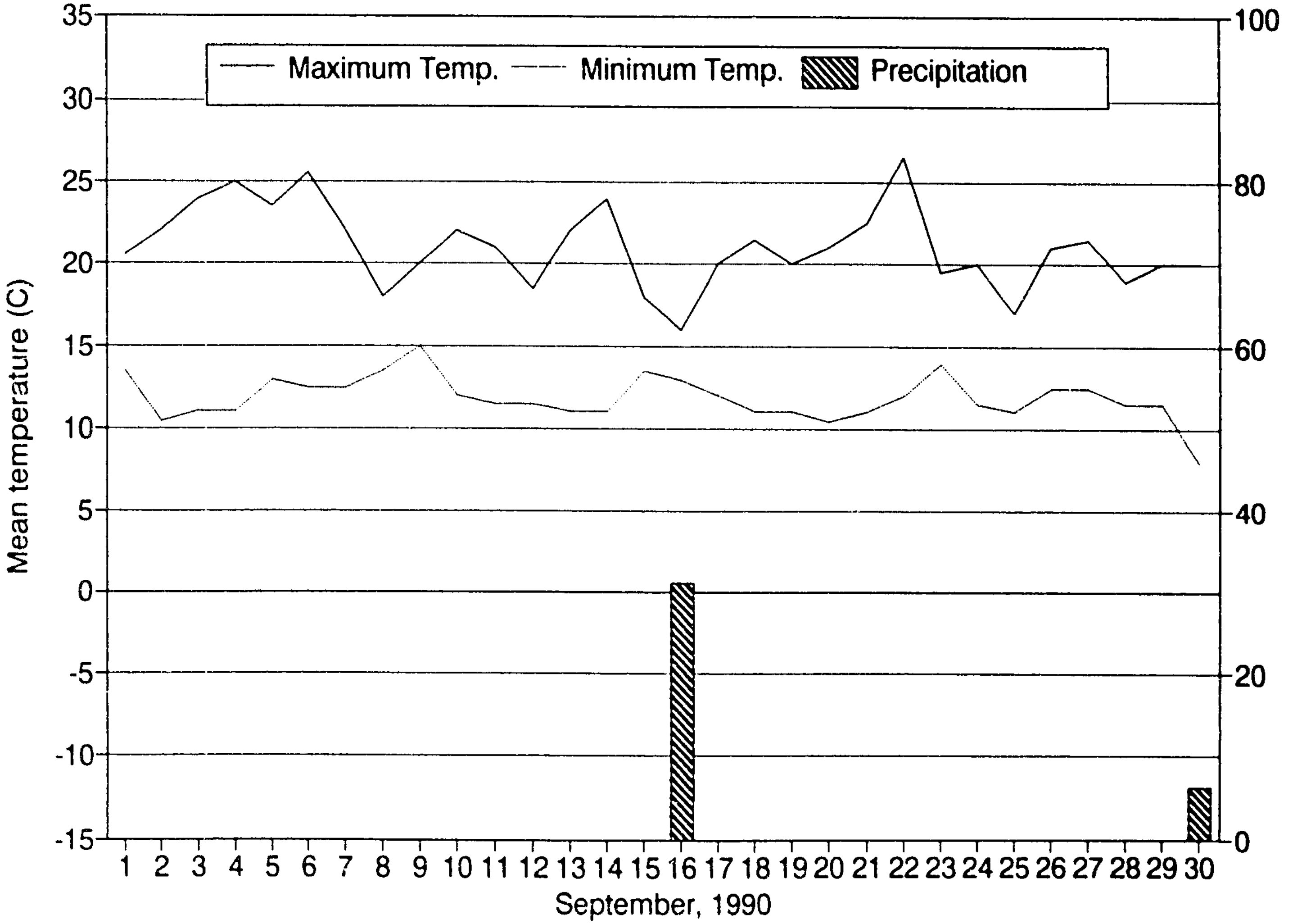

Figure B6 Lions Bay meteorologic data September. 1990

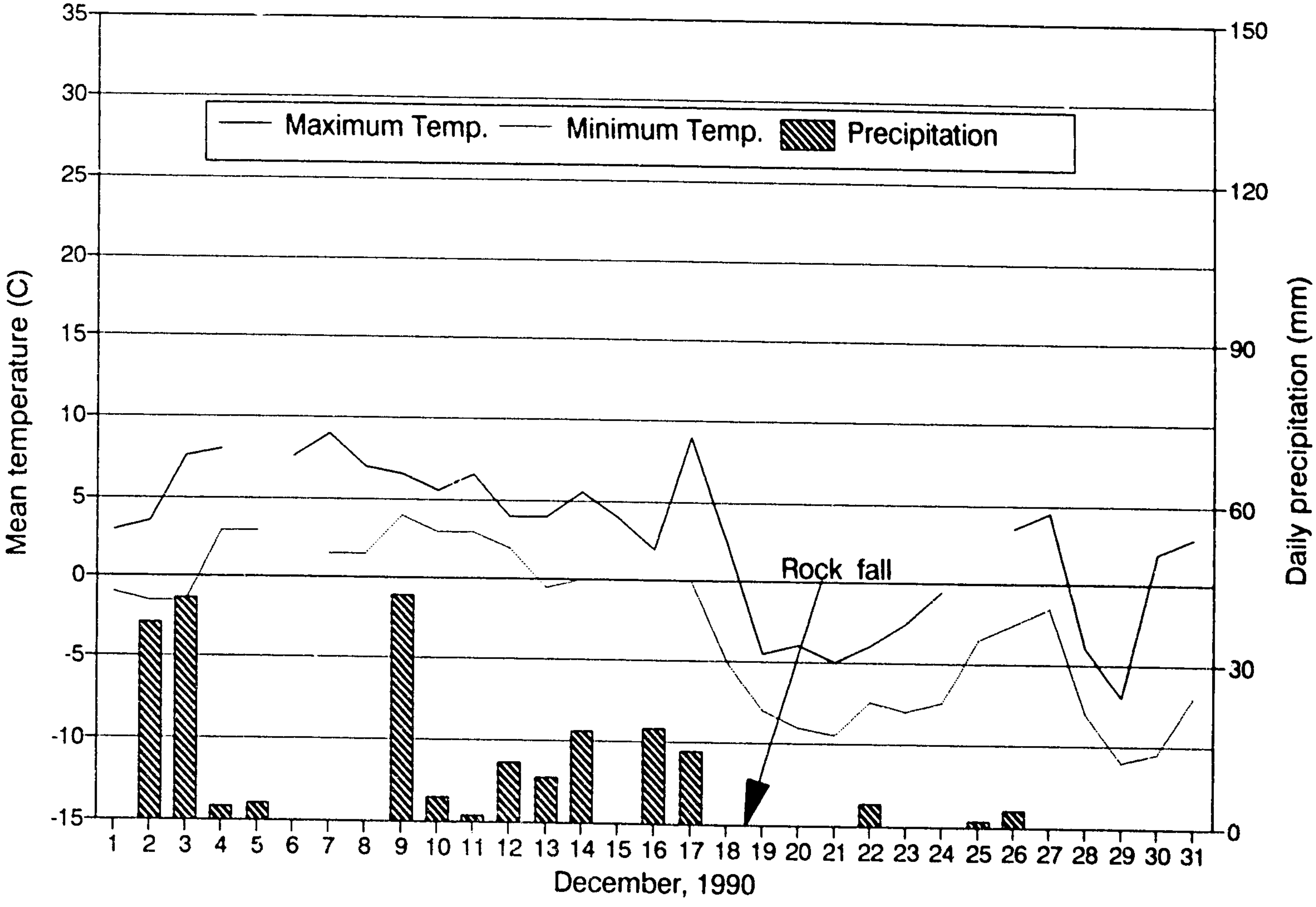

Figure B7 Lions Bay meteorologic data December, 1990

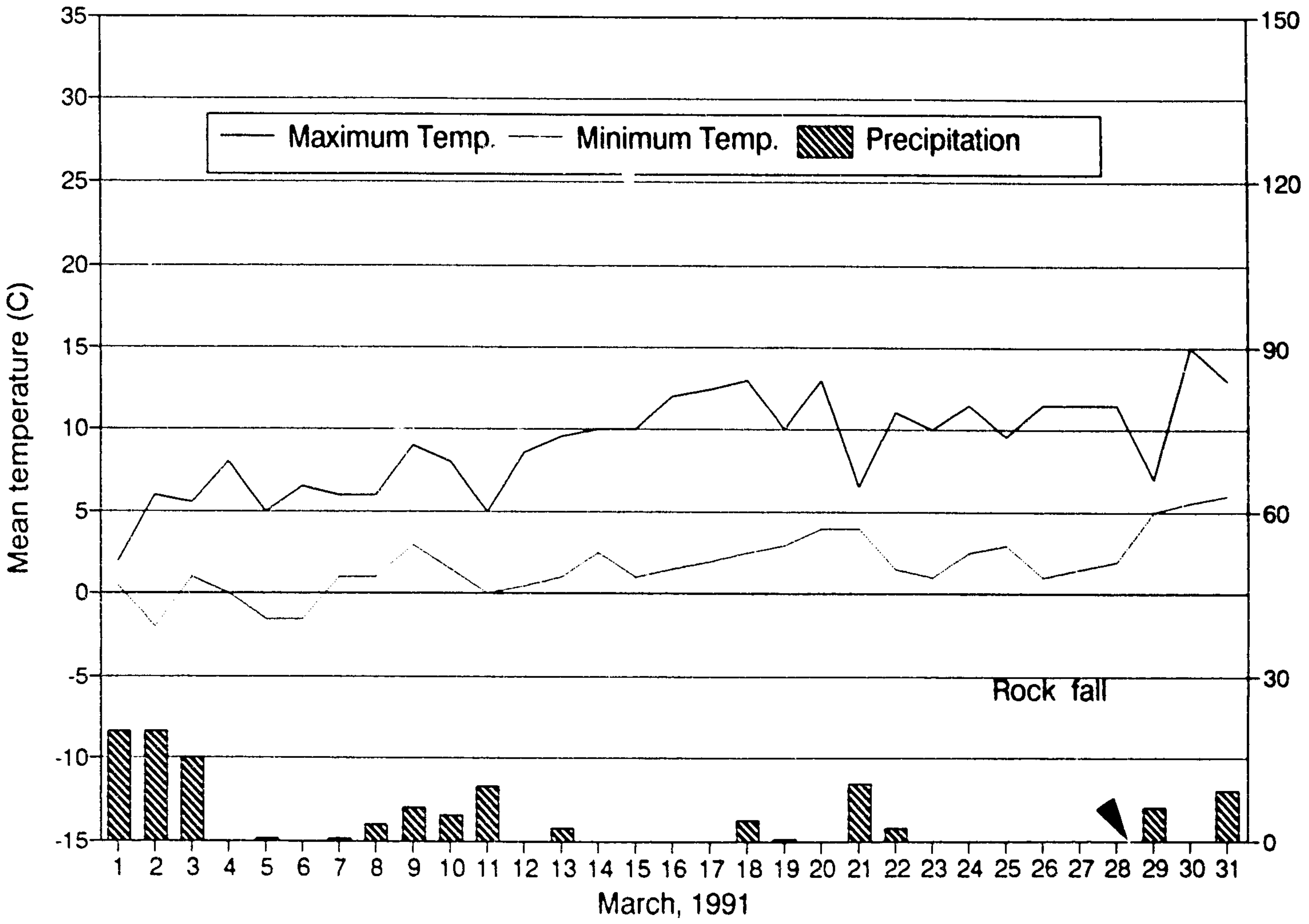

Figure B8 Lions Bay meteorologic data March. 1991

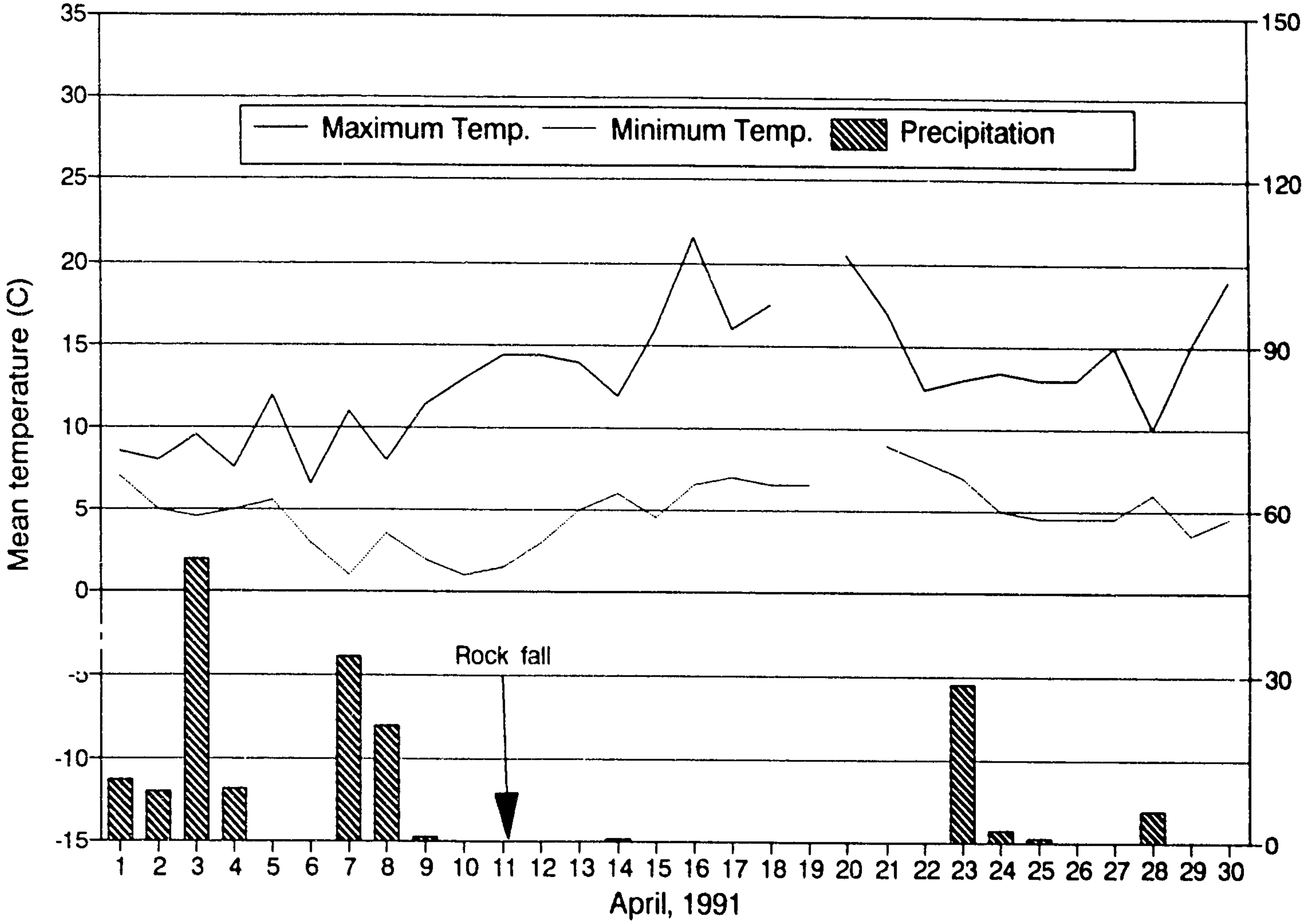

Figure B9 Lions Bay meteorologic data April, 1991