The role of catastrophic processes in the evolution of talus derived rock glaciers

by

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DEDICATION

To my parents for everything.

ABSTRACT

The role of catastrophic processes in the evolution of the talus derived form of rock glaciers is examined. Talus derived rock glaciers consist of interstitial ice and talus-like material and are thought to move by a creep mechanism due to plastic deformation of ice. The surfaces are a complex of flow ridges, transverse and longitudinal. Debris avalanches and slips are proposed to have significance in the supply of material and the development of the flow ridges. The processes are discussed and a simple dry friction flow model, incorporating several postulated movement mechanisms, is constructed. The feasibility of the catastrophic process is considered by comparisons between the model and the characteristics of talus derived rock glaciers in the Kluane Ranges of the Yukon. A framework of relations between catastophic and creep processes is outlined, and a scale of development is proposed in which creep is active at lower angles (rock glacier angles) and catastrophic failure is active at higher angles (talus angles).

RESUME

Nous avons étudié le rôle joué par les processus catastrophiques dans l'évaluation de glaciers rocheux de talus. Ces glaciers rocheux sont constitués de matériel s'apparentant à des talus et contenant de la glace interstitielle et dont on attribue l'écoulement à la déformation plastique de la glace. En surface on retrouve des crêtes longitudinales et transversales, constitués de matériel provenant d'avalanches et de petits-glissements. Un modèle simple d'écoulement avec friction à été élaboré et plusieurs mécanismes s'y rattachant ont été expliqués. Parmi ces mécanismes, celui basé sur le rôle joué par les processus catastrophiques a été examiné de près à l'aide d'une comparaison entre le modèle et les caractéristiques morphologiques des glaciers rocheux de la région de Kluane, Yukon. L'écoulement global des glaciers rocheux semble être lié à deux processus agissant a deux échelles différentes : d'une part, le 'creep' agissant sur les pentes faibles du glacier rocheux et d'autre part, les processus catastrophiques agissant plûtot sur les pentes fortes du talus.

ACKNOWLEDGEMENTS

The title page of this thesis includes the phrase ' by Michael Maxwell ', which does not even hint at the number of people and organizations which have contributed to the completion of the work; a more suitable terminology would be ' by Maxwell et al '. Support was provided in the areas of finances, theoretical discussions, logistics and psychological stability.

The Northern Research Group of the University of Ottawa and the National Research Council of Canada contributed financial support to the fieldwork, and Department of Geography Assistantships and Ontario Graduate Scholarships eased the financial burdens of the school years, all of which reduced life's pressures. Theoretical pressures were lightened by a series of talks with Dr. Don Shields, formerly of the University of Ottawa, Dr. John Harrison and Roy Sage of the GSC, Beth Sullivan of the computer applications section at the University of Ottawa, and Dr. Bill Nickling of the University of Guelph; I thank them again.

Parks Canada permitted the fieldwork to proceed in Kluane National Park and I am grateful for their interest. The logistical support from the Arctic Institute of North America at Kluane Lake was appreciated and the new friendships with Andy, Carol and family, and Phil and Claudette are an added treasure. I am also indebted to Cindy and Bonnie Pankiw for their skill on the keys, 'the Lok' and Sergio for their patience, and Lynne Warner for her advice and help.

My psychological stability received boosts from many directions the most memorable experiences being; the Pankiw gang for helping me retain, and lose my reputation; the Henderson House for having pity for a stray waif; the Grizzly Lunatics for teaching, amongst other skills, the joys of bottling forget-me-nots; Chris and the hot summer night swims; and the friends of Max for every little thing.

One person has contributed to all aspects of my work and there can be no way of returning all of his help. Peter Johnson provided an environment which has produced an education beyond solely the academic aspect. I am grateful for his knowledge, advice and understanding. For these, I thank him with my friendship.

> " All experience is an arch, wherethro' gleams
> that untravell'd world whose margin fades,
> forever and ever when I walk. "
>
> Tennyson

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Chapter I

INTRODUCTION

The term rock glacier, has invoked a misleading categorization of a landform feature which occurs in varying guises throughout the alpine regions of the world. The variety of mass movement features which are labeled under the general heading of rock glacier, can be of glacial or non-glacial origin, and may have only minor relation or similarity to a glacier. To expand the scope of study beyond this lingering glacier connection is the main purpose of the present research.

The postulate is that catastrophic processes of non-glacial origin may have significance in the formation of the talus derived type of rock glacier. Previously, concentration has centred upon processes related to ice deformation. There is poor understanding of the postulated, as well as the accepted mechanisms of movement. Fieldwork has provided information on the characteristics of rock glaciers, however, a comprehensive theory of the evolution of rock glacier features has not been formulated. Because of the difficulties experienced in field and laboratory work, a modeling approach will be used to aid in determining the possible effects of a catastrophic mechanism. The use of modeling permits the examination of a range of potential modes through which a process can act, thereby contributing to the understanding of the process/landform relation.

The thesis is organized to reflect the modeling approach as fully as possible. The first chapter introduces rock glaciers and their characteristics. The drawbacks of presently accepted theories are suggested and the difficulties of research highlighted. Finally, the modeling technique is discussed and previous associated work described.

The second chapter outlines the methodology employed, including the development and manipulation of the models. Chapter Three covers the results and analysis of the modeling work, and a discussion of the relation of catastrophic processes within a rock glacier evolutionary framework. To conclude, Chapter Four summarizes the research and the feasibility of the catastrophic process as applied to rock glaciers. References are dispersed throughout the chapters because of the diversity of fields which are involved. A general literature review is also incorporated near the end of Chapter One.

In the St. Elias region of Canada alone, the Canadian Glacier Inventory has identified 700 rock glacier features (Ommanney,1976). That such a common landform has remained difficult to interpret is a misfortune. The problems of connecting the accepted hypothesis of rock glacier origin with the observed feature, necessitates the consideration of other possibilities. Only by increasing the study base, can the active processes be married to the features, and a catastrophic mechanism is suggested by field evidence.

1.1 THE PROBLEM

A precise definition of a rock glacier is elusive due to the wide range of features which have been associated with the name. The nomenclature has actually resulted in an unnecessarily biased approach, due to the images and processes which are connected with the term glacier. Rock glaciers cover two main spectra of classification. They can be categorized by movement, and by composition. The movement spectrum is bracketed by cessation of activity (fossil forms), and by catastrophic motion. The composition spectrum has the limits, pure ice, and rock (Potter, 1972, and others). The majority of features termed rock glaciers display properties in the middle of these two divisions. Thus an 'average' rock glacier will contain a mixture of ice (interstitial or massive) and debris, ranging from fines to large boulders, and will indicate an apparent movement of for example, 50 centimetres per year. The evolution of the landform cannot be averaged similarly.

Rock glaciers are labeled by a variety of descriptive names, depending upon their apparent origin. Moraine rock glaciers (terminology - P.G. Johnson) are postulated to form in glacial moraine (terminal or ground) and are generally accepted to have ice cores (Whalley, 1974a, Ostrem, 1971). They are characterized by thick deposits of debris which cover the ice and appear as transverse ridges along the feature. The surface is marked by slumps and drainage pits and lakes (P.G. Johnson, 1974). Talus derived rock glaciers (terminology - P.G.Johnson) form at the base of talus slopes. The surfaces usually are a series of transverse ridges, although the sequences are sometimes cut by longitudinal ridges. Although most talus derived rock glaciers have not been checked, it is generally accepted that there are not ice cores, but that the talus material is 'cemented' by interstitial ice (Wahrhaftig and Cox, 1959). A search through the literature can yield at least a dozen other terms which are or have been used to describe variations of the landform (see Ommanney, 1976). To increase the complexity of nomenclature, rock glaciers are also categorized by their shape. Type names are self-descriptive and include spatulate, lobate and tongue-shaped.

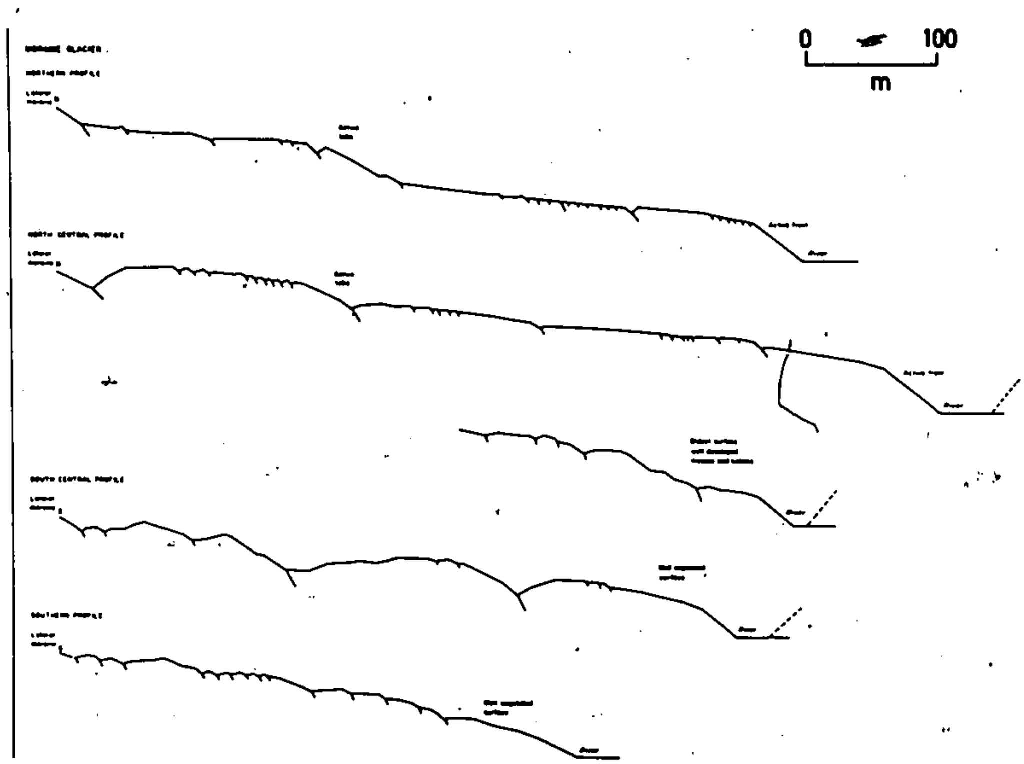
All of the landforms which are identified as rock glaciers display several similar features. The surface appears as a sequence of lobes, either transversely or longitudinally. These ridges usually assume an arcuate form and are often in a regular series down the landform. Active rock glaciers give evidence of the presence of ice, either interstitial or massive. Fossil rock glaciers usually indicate that a melting-out period has occurred. Typical dimensions of rock glaciers are listed in Figure # 1 and profiles of Grizzly Creek rock glaciers are shown in Figures # 2 to 5. Ommanney (1976) also includes tables of the lithology and movement characteristics of rock glaciers.

The processes of formation and movement adopted by the majority of researchers to explain the characteristics of rock glaciers are related to the presence of ice. Plastic deformation of ice is proposed as the significant process. In ice-cored landforms, the stagnant terminus or moraines of a glacier have activated, and the debris load affects the normal flow of ice, to cause the ridge sequences, as well as movement away from the source. This explanation is acceptable and can usually be borne out by field evidence. The case for interstitial ice features is harder to justify. The accepted postulate is that an ice creep mechanism is effective in spite of the lower ice content, and thereby produces the distinguishing characteristics. This process could be significant, but there is evidence that other processes may be active. The study of ice creep should not result in the exclusion of these other potential explanations. There are talus slopes which exist in areas where talus derived rock glaciers are present, which have not evolved into similar features (Smith, 1973, and observations by author in Kluane Range, Yukon).

LENGTH (metres)	WIDTH (metres)	FRONT HEIGHT (metres)	FRONT SLOPE (degrees)	GRADIENT (degrees)	THICKNESS (metres)	ELEVATION RANGE (metres)
1000	2000					
>2000	<300					
3-5000						
300-1600	150-3200	10-100				
			30	12-30		
91	3					
170	110	4	42			
1600						
180-365						
50-350	100- 900					
150-1300	75- 300					
60-1000	90-3000					
150-1500	60- 800					
2-5000						
1200	550				5-10	1860-2260
1600	200- 800				>30	
300	150					
1200	250				>10-20	
		30	45			
372	421.	21				1750-2090
979	305	25				1617-2050
667	1008	31				1488-1798
100- 850	150-1350					2181-2245
300-2100	100- 850					2219-2304
500-1300	250- 750					2201-2329
100-2100	100- 850					2235-2318
150-1150	150-1350					2173-2256
3-8000	400- 800			10		
300- 600	150					
		6-152	22-40			1737-2743
100-1000					15-45	
823				12		-1500
<430	<430					2135-2440
540	5000					
450-1000				5-19		1065-
1615	550	61	40			1830-
15	1					
800						

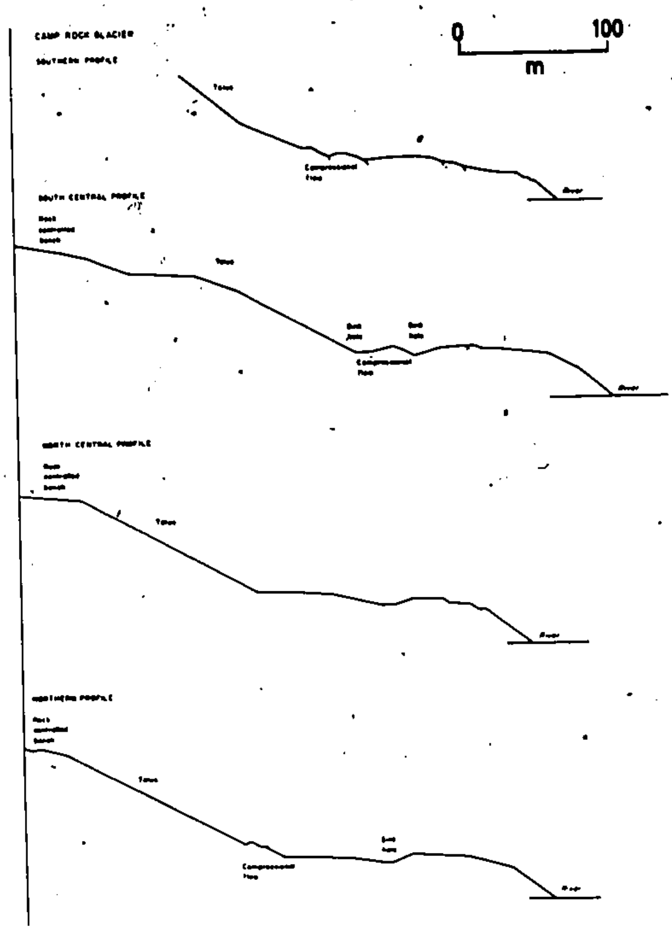
Note : From Ommanney (1976)

Figure 1: Rock Glacier Morphography



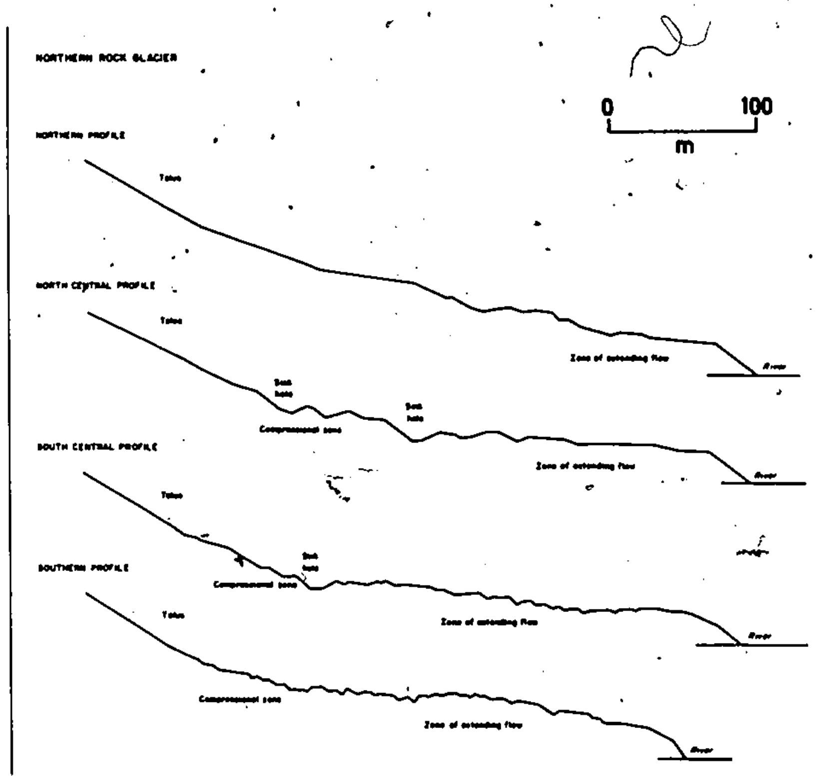
Note : from Johnson (1978)

Figure 2: Profile of Moraine Glacier - Grizzly Creek



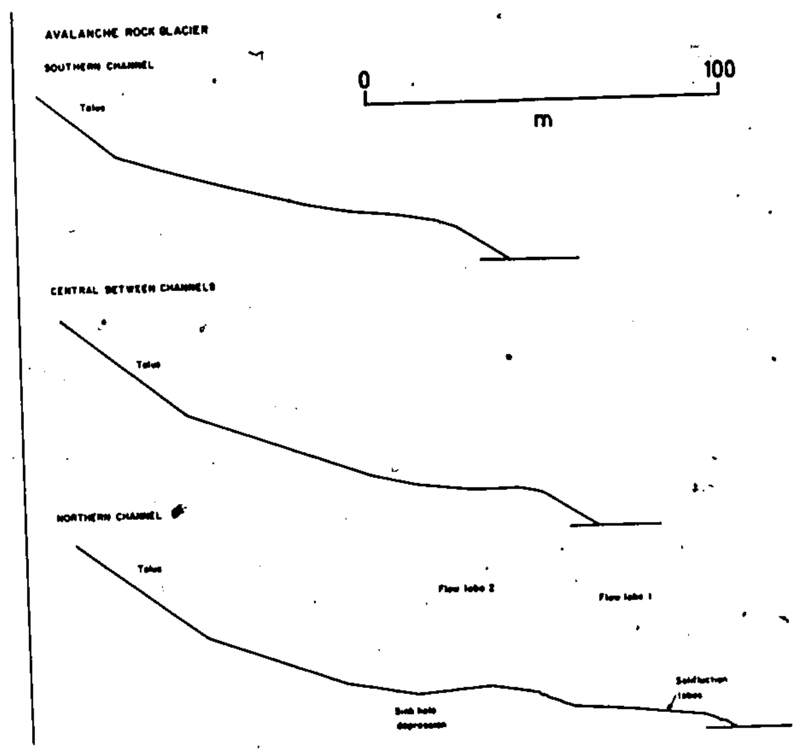
Note : from Johnscn (1978)

Figure 3: Profile of Talus Derived Rock Glacier - Grizzly Creek



Note : from Johnson (1978)

Figure 4: Profile of Talus-Derived Rock Glacier - Grizzly Creek



Note : from Johnson (1978)

Figure 5: Profile of Avalanche Rock Glacier - Grizzly Creek

As an alternative to the steady state creep mechanism, the hypothesis of this study is that catastrophic processes are significant in the formation and movement of rock glaciers. The catastrophic processes involve a failure of a talus slope (catastrophic implies a time scale which is short compared to the age of the landform). This movement of debris will be important in the formation of the rock glacier and directly, indirectly, or not at all responsible for the ridge pattern on the surface. A number of potential modes will be considered later. The drawbacks of the presently accepted theory will be discussed first, to justify the requirement for a new hypothesis.

The thesis concentrates on the category of the talus derived rock glacier, which contains interstitial ice. Ice-cored rock glaciers are satisfactorily explained by deformation of ice, although the precise effect of large debris loads is still under analysis. The talus derived rock glacier type requires further interpretation. It was suggested earlier that field evidence opposes the steady state explanation and that drawbacks exist in limiting study to alternatives based on ice creep. These aspects and others related to limitations of past geomorphological studies will now be discussed.

As stated initially, the name rock glacier is a misnomer, as the features can be of glacial or non-glacial origin. Limitations in past studies have resulted from a biased approach. The direction of research was destined to emphasize the importance of ice. Since the general tendency was to explain development by processes, similar to those active on glaciers, other processes (such as avalanching which was suggested as early as 1909 by Howe) were quickly dismissed. Researchers also attempted to classify landforms by climatic categories such as periglacial, glacial and arid. By classifying rock glaciers as periglacial (Embleton and King, 1975, Washburn, 1973), emphasis was placed on processes which were identified with periglacial climates, resulting in a form of tunnel vision.

The requirement to maintain open-minded concepts in geomorphological studies has become significant in recent years due to the increased interest in a process approach. A process approach considers the mechanisms which potentially occur or have occurred and what forms they will produce, then compare the results to field evidence (as opposed to the study of a landform and its characteristics with a subsequent postulation of its evolution). By this technique, the significance of different mechanisms in the evolution of a landform can be determined. Such a study includes a consideration of processes which are of importance in all climatic areas as they may have application.

This last point is clarified if the concept of evolutionary phases is accepted. When a landform was created, it did not necessarily appear as it does today. Extending the argument further, the environmental and other conditions did not have to be similar to those through the intervening period, or at present. It is feasible that processes which have become more significant since formation, have caused an evolution of the landform, which masks the original formative processes. It is vital to study a range of mechanisms when interpreting a landform. Since past research has often not approached from this open-minded concept, it is necessary to question the basic postulates of potentially misinterpreted landforms (White, 1971, Whalley, 1974b).

Determining the relationship between significant processes is also a source of difficulty in studying a landform. More than one process may be involved in the development of rock glaciers. A talus derived rock glacier can be supplied debris by a process which is independent of the movement of the rock glacier. The creep mechanism may be responsible for the movement of the ridges and lobes, but not for their formation (a number of formative processes will be postulated which have little relation to ice deformation). To separate the study of the processes active on the talus slope from those on the rock glacier is of major concern. Talus slopes are studied, and rock glaciers are researched, but the interrelationships are often not considered. Connections between different processes and features, which have previously been treated lightly, can result in a better understanding of the development of landforms, specifically rock glaciers.

An enduring geomorphological belief which has hindered research, is the acceptance of long evolutionary periods in landform morphology. With rising interest in catastrophic processes, the belief that landforms develop slowly over long periods of time is being questioned. The hypothesis of rapid change with periods of relatively slower acting processes, is now considered a distinct possibility. The general trend is akin to a move from continuum mechanics to quantum mechanics, although in geomorphological terms a combination of the two methods is more applicable.

The history of rock glacier research reflects the problems which have just been outlined. Studies which involve the observation of characteristics of the landform, and classification of the observed features are necessary to accumulate characteristic data, but to further the understanding of rock glaciers, research into the processes related to the formation and subsequent evolution is required. Until the study of Wahrhaftig and Cox (1959), significant processes were simply speculated with little laboratory or theoretical justification. Even into the past two decades the accepted creep mechanism has not been well theorized. Field observations which do not always justify the creep process will be examined[1].

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[1] One of the problems of rock glacier studies has been the difficulty in classifying the different categories, as exemplified by the recent dispute between Ostrem (1971) and Barsch (1971).

1.1.1 Field Evidence

The St. Elias Range in the Yukon Territory has a large population of rock glaciers which display a wide range characteristics. Work on a number of talus derived rock glaciers in the Grizzly Creek area initiated doubts about the accepted mechanisms of the feature's evolution. Although some of the counterpoints are specific to conditions in the area, similar cases exist in other regions, as they have been observed in the Canadian Rockies (author). Comparisons to other work are difficult because talus derived rock glaciers have not been extensively documented.

In the Yukon case the creep mechanism is less than satisfactory in explaining the observations. Figure # 6 shows a talus derived rock glacier (referred to as the Duke Talus Glacier) in the Duke River Valley of the St. Elias Mountains, Yukon Territory. The ridges can be identified clearly and show two distinct movements. The lower vegetated lobes appear to have been overridden by a later movement shown by the uncovered ridges. The feature displays the hourglass shape, identified with catastrophic failures such as mudflows and rock avalanches. The transportation of the debris has left an upper basin which interrupts the talus slope along the river valley. Near the right upper slope, a large deposit of talus-like material can be identified (also in background of Figure # 7). A talus derived rock glacier has formed from one debris slope but not from the adjacent one.

Figure 6: Duke Talus Glacier - Kluane Range, Yukon

Photo by P.G. Johnson

Figure 7: Slip Faces on Duke Talus Derived Rock Glacier   Photo by Max

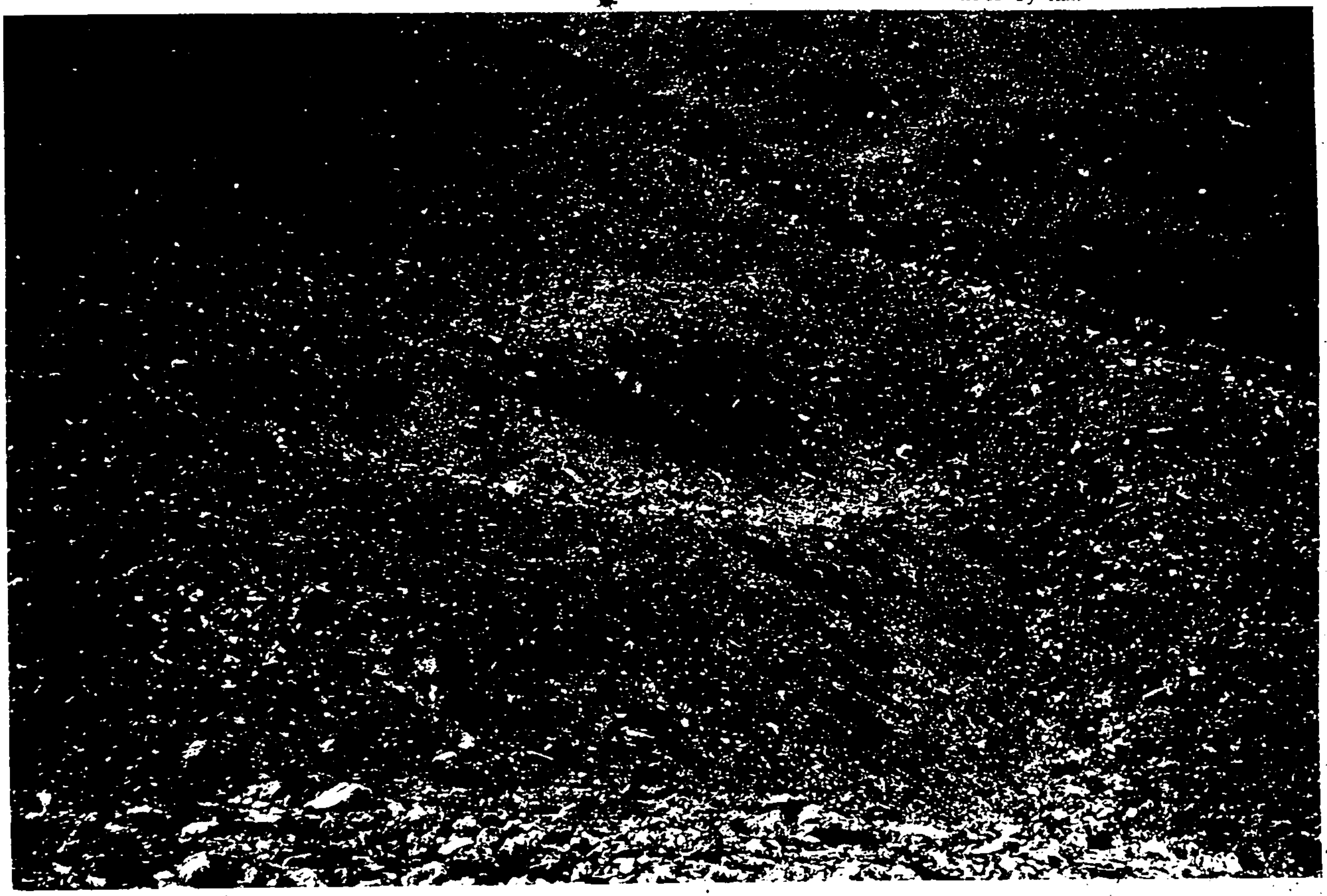

Figure 8: Slip Faces on Duke Talus Derived Rock Glacier

Photo by Max

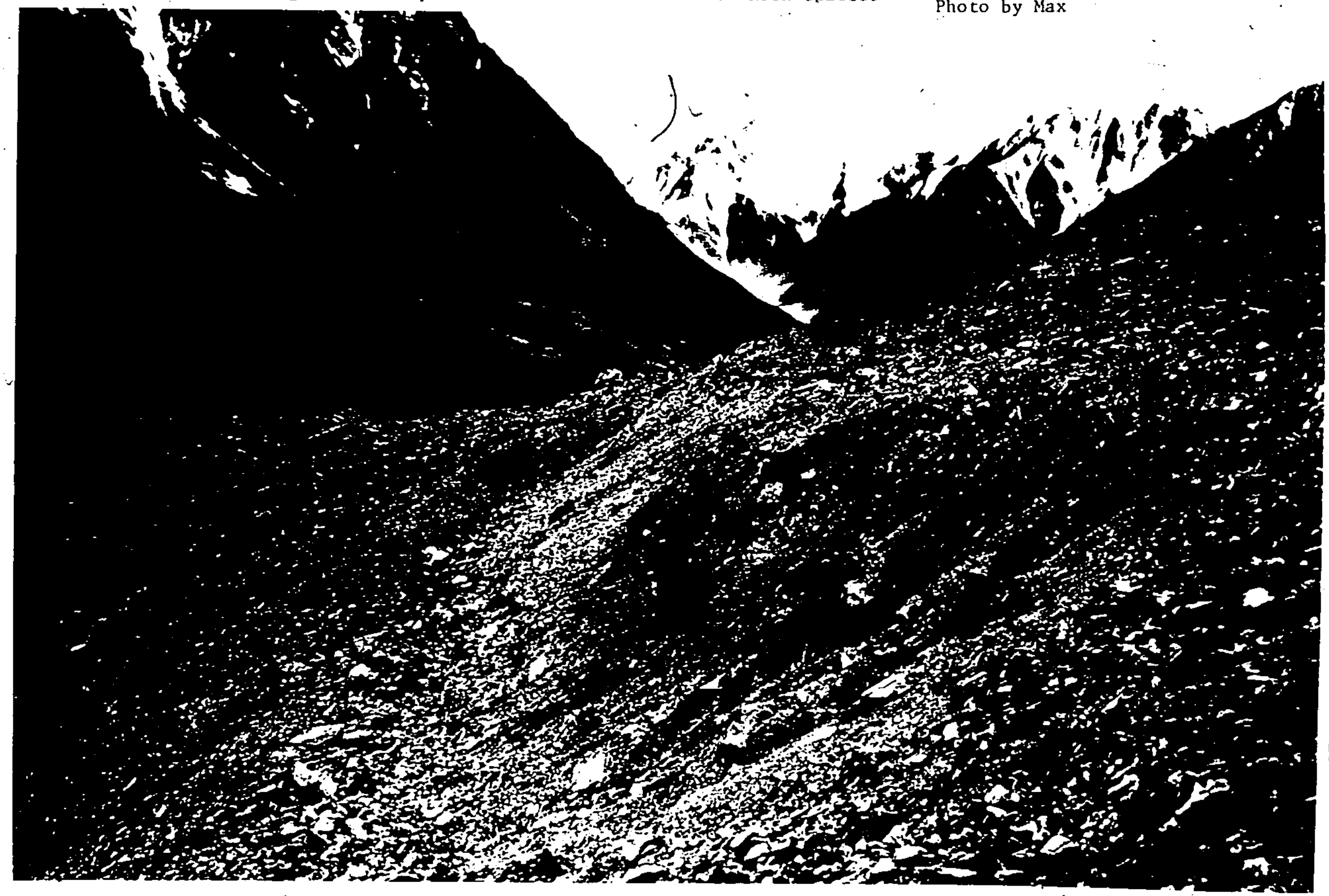

Figure 9: Failure Scar in Mine Tailings Dump, British Columbia Photo by John Harrison, GSC

Figure 10: Surface Contour of Mine Tailings Flow   Photo by John Harrison, GSC

Assuming that the Duke Talus Glacier has formed by a creep mechanism, the question arises as to why the talus to one side has not been affected. If the deposit was laid down after the flow of the rock glacier, then there should be new talus above the glacier. The upper part of the Duke Talus Glacier is a basin which contains only a small talus accumulation not on the scale of the deposit in question. (The cliff is not obviously different above either feature.) If conditions were similar then the creep mechanism would be expected to act equally on the slopes. It is difficult to speculate on a difference in conditions (composition, structural, or ground water) which is significant enough in the Duke case, to have restricted this equal action. Therefore, the conclusion is that a more selective process must be of importance.

The stability of a slope is determined by micro-conditions of the particular slope. These conditions can vary greatly even over short distances (metres) on, and in a slope. Consequently, the effects of an instability can range from small local slippage or shallow slides, to deep-seated failure. Catastrophic failure is a selective process and could account for the movement of one slope and not an adjacent one. Local conditions could have caused the avalanche to form the Duke Talus Glacier, while slight variations would have resulted in the stability of the adjacent slope. The appearance of the modern Duke complex can support the conclusion of the activity of a catastrophic process.

Reinforcement for the questioning of the creep mechanism exists in the absence of sizable areas of solifluction in the Grizzly Creek area. Solifluction and creep processes act in similar climatic conditions. Slopes are present in the area which should have been susceptible to solifluction during the formation of the rock glaciers. There is no evidence of major solifluction activity, which is a curiosity, if creep mechanisms had been active.

Furthermore, the creep mechanism is slope dependent in that it causes movement of material down a slope. Talus derived rock glaciers would therefore be expected to show deflections in a down-valley direction for the slow acting steady-state mechanism, especially where the gradient is steep. Air photos of the rock glaciers of nearby Duke and Bighorn Valleys show no significant down-valley deflection. As well the steeper Grizzly Creek valley shows no significant deflection of its rock glaciers.

The Grizzly Creek area rock glaciers all appear as a dual movement, the interpretation of which is difficult with the steady state hypothesis. After the first flow the feature became stable as the growth of vegetation indicates. The subsequent flow has encroached upon the initial flow. If conditions were suitable for a later flow, should the first flow not have been reactivated? The vegetation growth does not support that conclusion nor do other characteristics of the features (Smith, 1973, describes a similar dual movement, although he does not reject the creep mechanism).

The last and most significant observation of the talus derived rock glaciers is the presence of slip faces, most markedly on the Duke Talus Glacier (Figures # 7 and 8). The slip face indicates that a section of slope has moved along the plane that is bared. This method of movement implies a failure, or catastrophic process. Consequently, the consideration of a process other than ice deformation is supported even if it contributes solely to the formation of the lobes, and not the movement. The slip faces also prove that failure can occur on the talus slopes in significant scale.

A seemingly unlikely source of information are mine tailings dumps. These man-made landforms are accumulated by the dumping of large quantities of processed ore into extensive slopes of debris. The material is similar to that composing talus. The configuration of the slopes is also of the scale of mountain talus. Frequently, years after a tailings dump has been abandoned, massive avalanching can occur involving the movement of debris on the scale of a rock glacier (Figure # 9). Studies carried out on the resultant landform, have shown the existence of a ridge sequence along the slope. These ridges can be identified in photographs of a pit heap failure in the mountains of British Columbia (Figure # 10) and in other unpublished examples[2]. A series of photos of one failure (not illustrated) has shown a retrogressive sequence occurring over a short period (minutes) of time. Unfortunately, the studies into dump avalanches were concerned only with the reasons for failure and little concern was given to the resultant landform. It is possible however, to utilize the observations and extend them to the field examples in geomorphology[3].

The previous discussions have outlined the necessity for more extensive studies into processes, and the relationships between talus and rock glacier, formation and evolution, and debris supply and movement. The scope of this study does not allow full attention to be brought to all of these considerations. The role of the present research is to complement past work, by considering a previously dismissed mechanism in a new light.

1.2 CATASTROPHIC PROCESSES

It is evident that avalanching may cause the formation of single or multiple ridge patterns. Therefore it is possible

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[2]The discussions on tailings dumps throughout the paper, are based on personal communication with Dr. J. Harrison of the Geological Survey of Canada.

[3]Evidence for ridge sequences also has appeared in some studies on talus. Studies on small scale debris slides (Jahn, 1967, p. 218) show that individual slides moving downslope result in the formation of a ridge on the surface of the talus. Gerber and Scheidegger (1974, pp. 33-34) also refer to the stepped appearance of many talus slopes, in their study of small scale slips active on modern talus.

that a catastrophic mechanism can have a significant role in the formation of a talus derived rock glacier. Even if the ridge sequence is not a direct result of avalanching, the importance of debris supply by the mechanism cannot be overlooked.

The influence of the catastrophic mechanism can be considered in a number of potential modes which can explain the morphology of a rock glacier :

1. The first mode involves the supply of debris to the rock glacier. A large avalanche of the talus could result in the basic form. Processes such as creep, may then have caused the evolution of arcuate ridges.

2. The second mode is the formation of a talus glacier by the avalanche of a talus slope. The lobes would be created from this avalanche by a failure-related mechanism. The only role creep would have would be a possible subsequent movement of the glacier, or the emphasis of the lobes. The time scale of avalanching would be neglible to the age of the landform.

3. This mode would also involve the supply of debris to the glacier. It is possible that avalanching could provide material to the base or lower slopes of the talus. This build-up of debris could result in a creep process which would cause movement of the lobe down the slope. Subsequent lobes would be built in sequence.

4. The final mode is also a combination of the steady state and catastophic processes. The slips which exist at present may represent the initial formation of a lobe. The creep mechanism acts to transport the lobe down the slope.

It is emphasized that the creep mechanism is not being ruled out. There is a framework within which different processes have different proportions of action. The purpose of this study is to contribute to determining the internal parts of the framework. The above modes do not reject the creep mechanism, but emphasize that catastrophic processes can be of greater significance than has been accepted in the past.

1.3 FEASIBILITY OF CATASTROPHIC PROCESSES

Slope stability is of major concern to geomorphologists and researchers of various engineering disciplines. Theoretical studies seeking quantitative data are common to the engineering field, whereas geomorphology provides information on processes and the classification of natural slopes. The engineering studies provide an in depth theoretical basis and the reader is referred to these treatments (i.e. Harr, 1966, Attewell and Farmer, 1976). The following discussion will simply provide highlights of the general theory, which apply to this particular study.

The stability of talus slopes is not an overworked topic. Work on modern talus slopes show slope movements do occur (Rapp, 1960a, 1960b, Jahn, 1967), the majority being microscale, producing small avalanche tongues on the talus slopes or at the base. The theoretical basis for these failures can be developed, however the actual initiating force cannot always be identified. A 'typical' talus slope, consists of an upper layer of coarse material from which the fines have often filtered into the lower levels. The talus material rests upon a base of bedrock which is usually of relatively low permeability. Thus the situation is a highly permeable layer on top of a less permeable layer.

This situation is more complex when the influence of permafrost is present. In most alpine environments, a talus slope must be described as three layers. The uppermost is the active layer which can vary between one and several metres thick, depending upon annual variations and other characteristics. The second layer is the frozen talus, and finally the base layer is again the bedrock. Although each layer is not necessarily homogeneous, they are usually accepted as approximating homogeneity.

There are two major interfaces in this configuration. The shallower interface is the unfrozen material lying on the permafrost, and the deep interface is that between bedrock and talus. Samples of soil at depth are not easily obtained, but the lower frozen layer likely consists of fines and possibly larger materials of a consistency similar to the upper active layer.

Naturally occurring talus slopes of the above types can be compared to slopes which have been researched by engineers. Tailings dumps and earth-fill dams have characteristics similar to talus slopes (Personal Communications, Shields (University of Ottawa, Civil Engineering), Harrison). Unfortunately, causes of failure in these examples cannot always be identified or explained. Studies on frozen slopes with characteristics identical to talus are not common. It is possible though, to compare frozen and unfrozen talus to materials which have similar engineering characteristics. These comparisons have allowed geomorphologists and engineers to consider the mechanics of failures in coarse materials and to speculate upon the related processes. A summary of the basic theory of slope stability will facilitate further discussion*.

Two categories of forces can be identified as active on any slope. One type opposes failure and the other contributes to failure. The type that opposes failure can be summarized by a term known as shear strength, S. Contributing to failure are the shear stress forces. Researchers have attempted to deter-

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*The stability section is based on discussions by Carson and Kirkby (1972), Attewell and Farmer (1976), Harr (1966) and Skempton and Delory (1957).

mine relationships which can accurately quantify the different forces active on a slope. The accepted shear strength expression is:

$$S = C + (\sigma - u) \tan \varphi$$

S = shear strength

C = cohesion

σ = total normal stress

φ = angle of internal friction

u = pore pressure

This expression is based on an effective normal stress analysis and is a modification of Coulomb's original work. The importance of water can be determined from the pore pressure term, as the hydrostatic pressure is usually the same as the pore pressure (gases can also contribute).

The φ term is determined by the internal friction of the talus material and is dependent upon the plane friction between particles, and the interlocking of particles. Plane friction can be either static or dynamic, the dynamic term being less. Interlocking of particles is a function of size, density and angularity of particles. Both factors, plane friction and interlocking, are a positive function of the effective normal stress. Thus, an increase in the effective normal stress (i.e. with depth) will cause an increase in the angle of internal friction.

From standard engineering tests different angles are defined which are used in different analyses. φ_u is associated with the dynamic angle of sliding (dependent upon plane friction). φ_m and φ_r are determined from shear tests and refer respectively to the maximum strength and the residual strength of a sample. Over time the strength of a material tends to the residual strength so the φ_r is the more commonly used parameter for slope studies.

Another test which is used is the measurement of the angle at which a material will rest when it has been poured from a low height in the dry state. This 'angle of repose', approximates φ_r although there is controversy as to whether they should be equal (to be discussed)[5].

The cohesion of a material is a force which acts to hold the individual particles together. For fine-grained or solid materials, total force can be the result of electrical and chemical influences. For large-grained materials the cohesion is zero as

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[5]An important convention in discussing angles is the term coefficient of friction. This term refers to the tangent of an angle; for example the coefficient of kinetic (or sliding) friction which is equal to tan φ_u.

these forces are not significant. It is possible to consider an apparent cohesion, when the effective normal stress is high, as failure will occur across individual particles, but a corresponding decrease in ϕ can counteract this effect.

Pore pressure is the force which is exerted by the substance in the interstices, usually air or water. When a soil is under load, the weight is opposed by the pore pressure and the interparticle contact. In effective stress analysis the pore pressure, usually the pore water pressure, is used in predicting failure.

To determine the shear stress at a particular point in a slope, there is a straight-forward relationship using the weight of the overburden.

$$\tau = \gamma_s * Z * \cos(TH) * \sin(TH)$$

τ = shear stress

γ_s = bulk unit weight of soil

Z = depth to failure plane

TH= angle of slope

The simple conclusion is that there is a potential stress failure wherever stress exceeds strength. Unfortunately the theory is far from perfect. It is a fact that slab failure and deep seated failures occur in granular media (includes talus or talus-like material), but the phenomena cannot be explained by the above theory. A prime example of this inadequacy is tailings dump failures. The dumps are designed to safe standards, yet after a few years, stress cracks can appear which lead to failure. The occurrence is inexplicable even with hindsight (Personal Communication, Harrison).

Attempts have been made to apply the theory with modifications but the results are not universally applicable. Carson and Kirkby (1972) utilize a threshold slope approach to predict a maximum height, H_c, at which talus of selected composition, will be stable. Their work is based on Skempton and DeLory (1957) which was a study of clays. The latter authors noted that deep-fissured clays displayed cohesion which approached zero. Carson and Kirkby extended the work to cohesionless talus material. They have compiled tables which summarize laboratory work performed on various natural materials. The difficulty of utilizing their approach is that deep-seated failures are not predictable, because cohesionless materials are either stable or unstable by their analysis.

Gerber and Scheidegger (1974) attempted to adapt a similar approach to allow deep-seated failures. They suggest replacing the cohesion with a term which is the average shearing limit for the depth of the failure section. Unfortunately, they do not fully justify their suggestion except to claim that it works, but there is no subsequent verification. In another attempt Rouse (1975) utilizes an approach similar to Carson and Kirkby. He describes a limiting angle of slope assuming two-dimensional homogeneous material with cohesion approximately zero, and a residual shear strength represented by[6] :

$$\alpha_L = \arctan\left((1 - m * \gamma_w/\gamma_t)\ \tan \phi_r' \right)$$

α_L = limiting angle

γ_w = bulk density of water

γ_t = saturated bulk density of soil

ϕ_r' = residual angle of shearing resistance

m = position of phreatic surface

m = 1 for saturated slope

m = 0 for water table below failure plane

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[6]This equation is a result of algebraic manipulation of previously listed equations.

Rouse, however, states that the model works only to describe shallow plane slides (microslides).

Although only three examples have been outlined, they represent the general aim of previous studies, to model slopes to predict form. The ideas are based upon present conditions of slopes and are an attempt to explain present slope angles and small scale failures in talus-like materials.

One of the assumptions of this study is that a catastrophic slide, of sufficient extent to move a mass of talus equivalent to that of a rock glacier, was possible under conditions in the past. As outlined, present talus work cannot explain this assumption, in spite of evidence that large scale failures can occur. Furthermore, studies on permafrost slopes and rock glaciers concentrate on creep processes and are not adequate to apply to catastrophic failures (McRoberts and Morgenstern (1974), Wahrhaftig and Cox (1959)). Therefore, conditions which would permit an avalanche of suitable size, will be speculated.

A vital factor in rock glacier movement is the presence of ice, and specifically for talus derived rock glaciers, the interstitial ice. The major question in dealing with ice rich debris is whether the ice acts to increase the strength or decrease the strength of the mixture. It has been proposed that ice in small amounts will act as a cement, thereby increasing strength, whereas in greater concentrations the ice will flow plastically, thereby decreasing strength when under stress (Personal Communication, Williams, Carleton University). The critical proportion is not known.

If the interstitial ice influences a talus slope to increase the strength, then it is possible to consider a standard slope stability analysis for deep-seated failures, since the cohesion would not be zero. These analyses are discussed in Bishop (1955), Morgenstern and Price (1955), and in general engineering textbooks. The value of the ice cohesion factor is unknown, therefore within the scope of the present work, the applicability of such analysis is diminished. (Research is being done by W.G. Nickling at the University of Guelph to determine the engineering characteristics of ice/rock samples from Grizzly Creek talus derived rock glaciers). It is possible that a deep-seated failure can occur in a permafrost talus slope due to the cohesive influence of small amounts of ice, although little consideration has been given to this proposal.

Concerning the presence of higher percentages of ice, there is a possibility that initial yielding of the mixture due to the plasticity of ice, can lead to a catastrophic failure (creep to failure). With slow deformation stress can increase to a level where it exceeds the peak strength of the slope, and thus causes a sudden failure. This process can be observed on various slopes: 1. Rotational clay slips- Isle of Wight 1978 - Author 2. Mine tailings dumps - formation of stress cracks - Harrison. There is also possible evidence for this type of process on the Duke Talus Glacier, Figures # 7 and 8. The slip faces which are present do not demonstrate the accepted creep mechanism. The lower debris has obviously slipped along the plane of the bared face. Later discussion of this process will consider its significance in the environment of formation.

Rock glaciers are described as a periglacial phenomena existing on the fringes of glaciated areas, or forming during the retreat of glaciers. The conditions of glacial ablation involve relatively warmer temperatures and the presence of large amounts of meltwater. It is also feasible that one process of transferring heat energy to the glacier ice is through increased precipitation during the period of ablation. These conditions which exist during the probable period of formation are of major importance[7].

The possible causes which can lead to failure in slopes which when initially formed were stable, are of several categories. The first factor which can contribute to a failure is the presence of high pore water pressure. Although talus is normally highly permeable, two underlying impermeable layers have been suggested :

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[7]Jahn (1967) discusses these factors in dealing with modern day processes on Spitsbergen slopes.

1. the frozen material

2. the bedrock

When precipitation is excessive and melting is also contributing water, the 'worst condition' (Rouse, 1975, Carson and Kirkby, 1972) of parallel sub-surface flow and a perched water table could induce failure.

The second factor which can contribute to avalanching, is oversteepening. This state can occur if the slope is initially formed with the incorporation of cementing ice. Subsequent melting of the ice may not induce failure until the active layer has reached a significant depth. A more acceptable cause of failure may be the process of slow deformation to failure.

A third factor can be the reduction in strength of the material due to removal of support. As glacier ice ablates, large deposits of lateral and ground moraine are exposed on the valley walls. These slopes may remain unchanged, although they are not in a stable condition, until a triggering mechanism causes a large failure. The triggering process could be any of those previously suggested (creep, excess pore water pressure, deep-seated failure). In Figures # 6 and 7, steep talus slopes with apparently unstable faces (very fine material exposed on lower sides), exist to the right of the Duke Talus Glacier. It is possible that while the talus above the rock glacier failed, this deposit has remained in a condition similar to that in which it was exposed.

The mechanism of movement after failure is of major importance in modeling the flow. In contrast to steady-state flow, two processes can be of significance in a catastrophic failure. The first process is a liquid flow. If a sufficient amount of water is present, the debris will move downslope under viscous conditions. The formation of ridges, transverse or longitudinal are feasible in a viscous flow. The application of this process is unprecedented in predicting the form of a rock glacier from talus failure. Therefore to initiate the modeling work of rock glaciers, the second process of sliding is utilized in the construction of the model.

The sliding mechanism involves the movement of the failed section along the surface of the lower slope. Evidence for the sliding mode can be seen in Figures # 7 and 8 (the slip faces on Duke Talus Glacier). Gerber and Scheidegger (1974) also accepted the sliding mechanism in their analysis of modern talus processes (rolling is an extreme case of sliding).

Altough conditions on natural slopes may not be conducive to large-scale failure today, the conditions during the period of formation may have been different. Possible explanations for large scale failures in the past have been outlined in this section. The modern example of tailings dump failures may be evidence of a similar process. The characteristics of a slope created by man-made processes could more closely approximate slopes prior to glacier formation than comparatively recent naturally created slopes. The difficulties of the application of failure analysis to granular media, especially with incorporated ice, were outlined. Previous studies applying the failure theory are an attempt to determine maximum angles of modern slopes. This research is an attempt to evaluate the significance of the process of catastrophic failure and sliding, in forming talus derived rock glaciers. The suggested process of sliding will be utilized within a mathematical model to aid in the evaluation.

1.4 THE PROPOSAL

The evaluation of catastrophic processes as they apply to talus derived rock glaciers is a difficult task. A standard geomorphological approach would consist of fieldwork, analysis, and possibly laboratory studies. All of these aspects have inherent problems when they are employed in rock glacier studies. Fieldwork is essential to the understanding of any landform. The cataloguing of the characteristics of talus derived rock glaciers has mainly involved description, material sizes, and dimensions. Due to the remote location of most rock glaciers, major excavations are difficult, and coring is costly. Furthermore, the difficulty of obtaining undisturbed samples of the constituent material at depth has made the study of the characteristics of flow a tenuous one. The limitations of fieldwork have resulted in a lack of quantitative data for use in theoretical work. Characteristics of the surface layers do not necessarily apply at depth. Activity at depth is dependent upon the amounts of ice and percentages of fines and other material. The samples from upper layers will provide some indication of the engineering properties of the material, but the effect of depth remains significant and difficult to evaluate.

The problems of laboratory study extend from the above points. In the operation of shear tests, maximum size limits of material exist, but rock glaciers have a significant large rock composition (especially in the upper layers where samples are usually from). The determination of the load limits at depth has no previous predictive basis. As a result the application of the quantifiable data which results from laboratory work must be weighed carefully.

The difficulties of these conventional approaches to the study of rock glacier-related catastrophic processes, suggest the utilization of a modeling approach. Modeling permits the fusion of theory to field data to determine their compatibility. By a dynamic modeling approach, a variety of potential processes can be examined along with a range of observed data to identify significant processes. The limits of modeling result from the feasibility of the hypothesized mechanisms and the validity of the simplifications which permit model operation.

Any proposal to utilize modeling is faced with the inherent problems of such an approach. Since these drawbacks are covered extensively in the literature (Chorley and Haggett, 1967, Cole and King, 1968), just a short discussion will be provided to outline the particular points.

The most frequent argument against modeling is that it is too simplified. By describing a natural situation with a collection of statements, mathematical or English, the degree of complexity is decreased. If the complexity is included, then the model becomes unwieldy. The two points are quite valid but with a methodical scientific approach, a compromise can be achieved between these two extremes. The value of a dynamic approach is the allowance for modification of preliminary models which have not properly weighed the different aspects, to provide an improved reproduction. One goal of the modeling is to consider the correlation between the complexities of nature. In the case of talus derived rock glaciers, this correlation has not been determined by traditional studies, therefore modeling may provide an answer. One of the advantages of the techniques is that different aspects can be isolated, and in that way an attempt to determine their roles can be made. If the isolation of a process, for example avalanching, is questioned, then similarly so must our present scientific knowledge. Many of the theories of science are based on practical and abstract isolations of different observations. Modeling, thus, is just another step in the scientific method.

1.5 LITERATURE REVIEW

Before the specific technique of modeling talus derived rock glaciers is developed, a review of previous studies will be valuable. Since the present study is an attempt to relate talus slopes to rock glaciers ,a variety of disciplines can contribute to the fund of knowledge, including geomorphology, geology and engineering. Most of the studies do not directly apply to a modeling approach. A review however, can provide a look at the theoretical basis of a model, as well as justifying the values of input parameters.

With the number of disciplines that were reviewed, there was also a number of terminologies. An encompassing classification system for slope movements belongs to Varnes (1975). His classification system is duplicated in Figure # 11. The different catastrophic processes are covered within this table. For example, the avalanche mechanism of Mode # 1 would be a complex movement, combining flow and slide, whereas the debris slips which were discussed, will be a subsection of debris slides.

Work on natural slopes in engineering will be the first area examined as most geomorphological studies are based on different engineering papers. The classical engineering paper is Terzaghi (1950), 'Mechanism of Landslides'. This paper is an extensive treatise on the engineering basis for mass movements. Terzaghi distinguishes the engineering difference between creep and land-

<table>
<tr><th colspan="3" rowspan="3">TYPE OF MOVEMENT</th><th colspan="3">TYPE OF MATERIAL</th></tr>
<tr><th rowspan="2">Bedrock</th><th colspan="2">Engineering Soils</th></tr>
<tr><th>predominantly coarse</th><th>predominantly fine</th></tr>
<tr><td colspan="3">Falls</td><td>rock fall</td><td>debris fall</td><td>earth fall</td></tr>
<tr><td colspan="3">Topples</td><td>rock topple</td><td>debris topple</td><td>earth topple</td></tr>
<tr><td rowspan="3">Slides</td><td>Rotational</td><td></td><td>rock slump</td><td>debris slump</td><td>earth slump</td></tr>
<tr><td rowspan="2">Transla-
tional</td><td>few units</td><td>rock block glide</td><td>debris block glide</td><td>earth block glide</td></tr>
<tr><td>many units</td><td>rock slide</td><td>debris slide</td><td>earth slide</td></tr>
<tr><td colspan="3">Lateral Spread</td><td>rock spread</td><td>debris spread</td><td>earth spread</td></tr>
<tr><td colspan="3" rowspan="2">Flows</td><td rowspan="2">rock flow
(deep creep)</td><td>debris flow</td><td>earth flow</td></tr>
<tr><td colspan="2">(soil creep)</td></tr>
<tr><td colspan="3">Complex</td><td colspan="3">Combination of two or more principal types of movement</td></tr>
</table>

Note : From Varnes (1975)

Figure 11: Slope Movement Classification System

slide, and provides a terminology (fundamental strength - stress at which creep begins, compressive strength - stress at which shear failure occurs). As well, he separates the processes responsible for landslides into external changes which alter the stress, and internal changes which alter shear strength. The other highlight of Terzaghi's paper is his discussion of the effect of water; the important points of which are :

1. only small amounts of water are required to lubricate a slide
2. the weight of water is generally minor
3. water dissolves binders
4. water increases pore pressure which reduces shear strength

Terzaghi uses the standard equation for strength of soils :

$$S = C + (P - h * w) * \tan \varphi$$

C=cohesion

P=pressure per unit area at a given point P of the potential slide surface due to weight of water and solids

h=piezometric head at P

w=unit weight of water

φ=angle of sliding friction for the surface of sliding which is based on Mohr-Coulomb failure criteria. The Terzaghi paper is important in that much subsequent work is based on the premises of the study.

The application of the different equations of stress and strength to soils can be understood by looking at standard soil mechanics texts, such as those previously referenced. These books discuss the theoretical basis of the accepted applications of failure criteria (concentrated chiefly on Mohr-Coulomb criteria which accepts the relationship between stress and strain rate, that their principal axes do not coincide). Difficulties arise in the extension of theory to some cases of failures in the field however, as exemplified by the pit slope failures which cannot be explained by present engineering theory. A determinant application of the theory does not alway give a correct situation. Consequently a stochastic approach is often used.

A probabilistic approach is the basis for a set of stability analyses on slopes of different classifications, which have been compiled by the Geological Survey of Canada. The analysis which is of interest to this study exists as a computer program, GENSAM, which can determine the most probable failure surface for a given slope, or will find the probability of failure for a given slope (the slope characteristics for the input to this program are similar to talus). Although initially this analysis appeared to be useful, the difficulties of field studies on rock glaciers, which were discussed earlier, prevented the evalution of necessary slope characteristics for input to the program. A further consideration of significance is that the conditions of the modern slope are not necessarily suitable to the formation of rock glaciers by a catastrophic mechanism. Because of the lack of valid input data, the GENSAM program was not utilized.

The pertinent engineering articles can be divided into the theoretical and laboratory studies of cohesionless soils, and the practical studies of actual mass movements. The main problem is that very little work has centred upon natural failures in cohesionless soils. On the theoretical side, papers such as Bishop and Skinner (1977) or Komamura and Huang (1974), are of value to the improvement of theory but have not filtered into field applications. Laboratory work such as Drescher (1976), 'An experimental investigation of flow rules for granular material using optically sensitive glass particles' (and other work by disciples of de Josselin de Jong) may prove useful if experiments can be adapted to mass movements in natural slopes, however that will be in the future also.

The practical studies are often too site-specific to supply information, beyond basic theory, to rock glacier or talus research. In the case of work situated in permafrost areas, the emphasis has been on creep mechanisms. Field studies such as McRoberts and Morgenstern (1974), outline the creep of frozen soil on permafrost slopes. The present theory of this process is summarized in books by Vialov (1965) and Tsytovich (1975). The problems of the application of steady-state flow to rock glacier features in the Grizzly Creek area have already been highlighted. Thus these engineering studies are of interest to the overall process framework but not specifically to the catastrophic models.

Geomorphological and geological field and theoretical studies complement the engineering work with more practical considerations. The studies of rock glaciers have already been referred to in the description of the feature's characteristics. The first comprehensive study of rock glaciers was that of Wahrhaftig and Cox (1959). They examined over 200 rock glaciers in Alaska, classifying a range of characteristics. They concluded that rock glaciers are a matrix of debris and ice moving by an ice creep mechanism which is responsible for the surface contours. The introduction is a summary of previous related work as are those of the more recent articles of Potter (1972) and Whalley (1974a). Ommanney (1976) also has compiled an overview based on Canadian studies (as part of the Canadian Glacier Inventory). All of these papers are valuable in presenting the range of hypotheses of rock glacier formation.

The first major article to propose exclusively a landslide mechanism was Howe (1909). Studies since then have considered catastrophic processes but have implied their importance only for debris supply. Barsch (1976) suggests that an avalanche or series of avalanches (snow or rock) may provide debris to the head of a rock glacier. Subsequently this deposit may undergo a steady-state flow to form a new lobe (similar to Mode # 3). Smith (1973) rejects the landslide process in discussing the extensive talus derived types of his study area, because he feels that they do not resemble landslide deposits. However Mathews and McTaggart (1969) discuss the resemblance of the Hope Slide of British Columbia to rock glacier features. The form of the mine tailings failures also show a set of ridges. Finally, Whalley (1974a) supports the role of rockfall in supplying debris and influencing flow of the Arapaho Rock Glacier (an ice-cored type).

Rock glacier studies have concentrated on the ice-cored feature with occasional reference to the talus derived type (exemplified by Outcalt and Benedict, 1965, with one page out of seven devoted to the feature). The problem was the classification of different types of rock glaciers. Wahrhaftig and Cox (1959) reject the ice-cored features and Whalley as recently as his 1974a article rules out the ice/rock matrix flow of a rock glacier. Corte (1976) tried to solve some of the classification problem by summarizing past terminology, grouping the talus derived types identified in other studies (Outcalt - valley-wall type; Potter - ice-cemented type; Barsch - talus slope type).

It still has not been resolved whether ice-cored rock glaciers and talus derived rock glaciers are the result of similar processes. This study proposes a mechanism which can be of application in both cases, although to different degrees.

The talus derived type requires the relation of two landforms with potentially two categories of active processes. Unfortunately applicable studies are few. Smith (1973) provides the most extensive comparison between the contributing talus and the resulting form. Extensions of the features range from 450 metres to 1000 metres with a possible relationship to headwall height. He describes characteristics similar to Grizzly Creek landforms (i.e. up to 10 metre lobe heights, dual movements with a lower inactive vegetated part, transverse arcuate ridges, and a slope break from the talus to the rock glacier). Other articles with direct application are Barsch (1971) and (1976) which describe talus derived types and speculate on the processes of formation. Other studies of rock glaciers are not of particular value to the present work and are summarized well by Embleton and King (1975), and Washburn (1973).

Talus studies provide characteristics of modern slopes and include stability analyses with consideration of the degree of significance of different processes. The classical study which attempts to relate description to processes is Rapp's 1960b paper. Rapp discusses the talus slopes of Spitsbergen under an extensive range of headings. Unfortunately no rock glacier features are discussed.

The major geomorphological work on slopes in the past two decades (theoretical and practical) is attributed to Carson and Kirkby (1972) in a variety of papers. Their book provides a summary of field and theoretical studies into slope stability. Carson (1971) bases a study on the determination of threshold slopes. He believes that above a certain angle of slope (depending upon the characteristics), rapid mass movements will occur. The value of Carson's work to this study is the calculation of the threshold values for slopes of various composition, which aid in determining input values for the models. Rouse (1975) and Rouse and Farhan (1976) use an approach similar to Carson and find instability at different angles on dry and saturated slopes in their study areas.

A number of names appear commonly in recent combined field and theoretical studies. They are Gardner, Gray and Luckman and less frequently Bones and Chandler. The problem with all of these studies is that they discuss modern processes of mass movement which do not involve large scale failures. Again the studies do discuss basic theory and provide justification for input data.

On the theoretical side, there are a number of studies which deal with slope angles and processes. Statham does laboratory work to determine porosity and angle of repose and does include the distinction between that angle and the angle of internal friction[8].

A well-noted author who has made an attempt to theoretically explain slope processes is Scheidegger. Talus processes are examined in a number of publications (Gerber and Scheidegger (1974), Scheidegger (1961)). He predicts that there is a length of slope that can fail which is determined by the angle and a critical height ($X=h_c/\sin\beta$, where β is the slope angle). To obtain a critical height a stability factor for a slope is derived from the stability curve analysis of Fellenius (1948). He then considers the dynamics of debris slides. The problem with his analysis is that a slide, due to its initiating mechanism must have an initial kinetic energy. The value is difficult, if not impossible to evaluate, unless a slide is observed. One value of the work is the use of coefficients of sliding and rolling friction which are evaluated by predicting that slides do not reach the bottom of a slope (which is not necessarily true). The application of the appropriate values from the 1974 article will be considered in the evaluation of the working models.

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[8]Carson (1977) and Statham (1976) disagree on the measurement and significance of these two angles. The articles will be discussed further in Chapter Three. The application of Statham's work is limited to providing characteristics of talus.

The final studies to examine, are those covering the modeling of slopes. The first category in which an extensive amount of work has been done, is the evolution of slopes. Work by Kirkby (1971), Young (1972) and Ahnert (1970) utilize the computer to produce profiles of slope form by assigning rates of erosion for different denudation processes. This type of study does not adequately consider the movement of the material however, only the overall slope profile. Scheidegger (1961) outlines slope form modeling but again the major concern is the profile.

Some interesting research was completed by Thornes (1971). He postulated that a scree slope can be an example of a queue. By applying queuing theory, he examined the effects of various input and output states on features observed in different areas. This work also is mainly concerned with the final profile of the slope and the method does not appear to be adaptable to explain the features of a rock glacier.

The value of previous studies is basically restricted to providing representative talus slope characteristics. The models which are developed assume failure based on the arguments discussed in this chapter. The movement of the failed section follows the laws of physical dynamics. Input is based on sample values derived from the literature and the rock glaciers of Grizzly Creek. Chapter One has introduced the talus derived rock glacier. The possible roles of catastrophic processes and the problems of past studies and interpretation by accepted mechanisms were outlined. The modeling of the postulated processes is the topic of Chapter Two.

Chapter II

METHODOLOGY

The first chapter has introduced the study of rock glaciers, along with the difficulties that have arisen in the interpretation of talus derived rock glaciers. The shortcomings of present knowledge and past research were outlined and a new approach suggested. By examining catastrophic mechanisms within models, it is hoped that the relation between different processes, within the formation and evolution framework of talus derived rock glaciers, can be predicted.

This chapter will describe the development of a variety of models in an attempt to synthesize the creation of a rock glacier. The emphasis is on preliminary model construction to consider the significance of the catastrophic processes. The models will provide a basis for future work which will incorporate the range of processes, from steady-state to catastrophic.

The first part of the chapter will discuss the formulation of the initial working model. After a step procedure has been outlined, the model will be constructed, then the input, output, and necessary assumptions will be examined. The initial model is modified to incorporate a number of mechanisms of flow. The explanation of the models and the assumptions made is covered in the following chapter on results. The results of the movement model are required within the subsequent models, consequently, they are discussed partially within this chapter.

2.1 MODEL DEVELOPMENT

The formulation of a working model for any system of natural processes must be methodical. That is, ideally it should be reproducible, and to achieve this goal a stepped procedure from theory to model is necessary. Yet, once the model has been designed flexibility must allow modification to be made, especially when using a computer, or there will be a gap between reality and the reproduction. Such a dynamic approach is covered in Merriam (1976).

The first step is the development of a conceptual model which will initially outline the aspects to be examined. Incorporated within this first step, or if necessary as a subsidiary step, a word description of the model is helpful. These first steps serve as a statement of the problem, but also provide the basis for the model, so they must allow adequate continuity from reality to model and back to reality.

For a computer model especially, the next steps are critical, the discretization of the English description. Discrete word statements must be formulated and placed in the correct sequence for manipulation. These word statements should concisely outline the steps to be followed. Secondly, these word statements should be altered to a sequence of mathematical statements. These discrete mathematical statements describe the processes which are being modeled, and also provide pivotal steps which determine the path through the rest of the model. The formulation of the discrete model involves the initial application of engineering theory, so it is dependent upon the present state of the art.

The next step is to construct a working model from the discrete mathematical statements. To link together the statements, assumptions must be made so that the model provides a consistent mathematical and physical sequence to describe the selected process. This step is the most subjective part of modeling, moreso in utilizing a computer for calculations. (The problems of subjective modeling are well-documented elsewhere (Chorley and Haggett, 1967; Cole and King, 1968) and were referred to in the first chapter.) The computer step is a technical one, which is limited by the earlier model design, but which can be improved through a feedback mechanism from the subsequent analysis. Thus, while incorporating the simplifications, later modifications allow the initial model construction to approach the ideal of natural process action. This factor is the crux of dynamic modeling and is the subject of the next step.

The importance of a dynamic approach now becomes essential to good modeling. The analysis of the results of the computer work is not the final step. Once the output has been examined, modifications which will permit improvements, must be incorporated. Upon alteration, further computer work will provide further analysis and then further modifications. By this iterative procedure, it is possible to achieve a more realistic model. The complexities and interrelationships of the processes can be improved from the basic model to better relate to actual observations.

The final analysis and conclusions must include an objective evaluation of the applicability of the model. This evaluation will aid in determining the significance of the results of a model. The results must correspond to the initial model goals. If certain aspects result which were not expected then their validity must be confirmed. That is, a model can be expected to produce results which are consistent with the theory but which may not occur in reality. The sifting of results and their relation to reality is crucial to the effectiveness of modeling. Through the isolating nature of models, results may not coincide with actual observations. But, in this way, models also provide information which does not arise from standard analysis. By careful examination of the results of model manipulation, significant characteristics can be determined, which contribute to the interpretation of the selected landform. This unique quality of modeling is the purpose of utilizing this approach to aid in understanding the evolution of talus derived rock glaciers.

The above procedure was employed to design the models which were utilized in this thesis. Initially a deterministic model was designed by the sequence of steps. The deterministic model was modified to produce the movement characteristics of different postulated catastrophic processes. The theory of each model will be outlined, then the selection of input parameters discussed. The assumptions necessary to simplify reality will be integrated with the model formulation, but the evaluation of each will be considered in the next chapter. The detailed mathematical, theoretical and computer procedures are included in appendices. The first model is the preliminary one.

2.2 PRELIMINARY MODEL

The initial model is deterministic and calculates the dynamics of a slope failure. The failure is modeled as a slab-type. In all of the modeling the failure is assumed to occur. The first simple model utilizes the basic laws of Newtonian Physics to study the movement of a slope which has failed. The characteristics of the slope will be described now, by following the step by step model formulation.

2.2.1 Conceptual Model

A talus consisting of homogeneous material exists at an angle, TH. The conditions on the slope are such that failure can occur. A failure will cause a section to move downslope according to the laws of physics (dynamics). The movement is a dry friction type.

2.2.2 Word Description

The slope of angle TH, can be described on a two-dimensional x-y axis. It will have a related height and slope length, one of which must be defined, the other being subsequently calculable. Since failure of a section can occur, the extent of a failure must be defined. To permit this, the slope will be sectioned by defining a depth and length of failure. Each section can be failed and the movement can be determined from physical laws. When failure occurs, there are two forces acting on the section, gravity and friction. The section will move along the talus slope and possibly on to a horizontal base.

2.2.3 Discrete Word Statements

1. The slope exists at an angle, TH, with a related height and length. The x-axis is the base of the slope and the y-axis is equivalent to the headwall.

2. A failure occurs of an extent determined from the slope length and the number of failure units. The

depth is defined. The failure units will be rectangular in the simple model.

3. The section moves down the slope under the influence of two forces, gravitational and frictional.

4. The movement includes that part which is along the slope and a possible extension onto the horizontal base.

2.2.4 Discrete Mathematical Statements

The mathematical basis of the following equations or definitions is outlined in Appendix A and illustrated in Figure # 12. For details of the model, refer to the Appendix.

1. The equation of the slope line is:

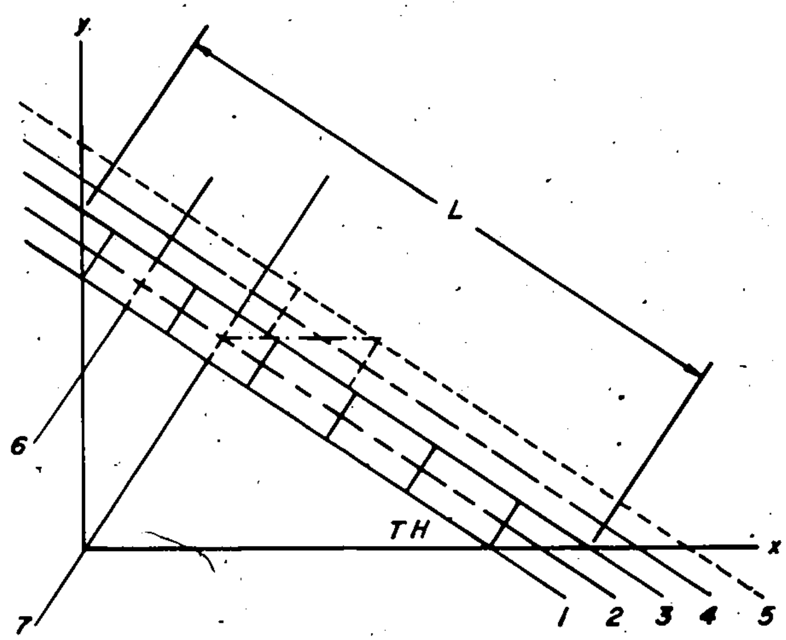
y=-H/HL*x+H   where H=height of slope
HL=horizontal length of slope
note: H/HL=tan(TH)

2. To define the sections, the equations which locate their boundaries, and centres of mass will be listed (refer to Figure # 12).

a) Lower Boundary:

y= -tan(TH)*x+(H-D/cos(TH))   where D=depth of failure

FIGURE 12 — MODEL SLOPE



Equations of Lines

1 Y=SL1*x+H-D/cos(TH)
2 Y=SL1*x+H-D/(2*cos(TH))
3 Y=SL1*x+H
4 Y=SL1*x+H+D/(2*cos(TH))
5 Y=SL1*x+H+D/cos(TH)
6 Y=SL2*x+H-D/cos(TH)-W/(2*sin(TH))
7 Y=SL2*x+H-D/cos(TH)-(3*W)/(2*sin(TH))

b) Centre line (parallel to slope line)

y= -tan(TH)*x+(H-D/(2*cos(TH))

c) Centre line of each failure unit I, perpendicular to the slope.

y=x/tan(TH)+(H-D/cos(TH)-W/(2*sin(TH)))

d) Centre line of failure units, after failure (parallel to slope).

y= -tan(TH)*x+H+D/(2*cos(TH))

3. To determine the movement of a failed section, the force and energy considerations are required.

a) Forces on a section.

FU=FG-FF   where FU=force on a unit
FG=force of gravity
FF=force of friction

FG=M*G*sin(TH)   where M=mass of the unit
G=gravitational constant

FF=MU*FN   where FN=normal force
=M*G*cos(TH)
MU=coefficient of friction

b) Energy Considerations

Potential Energy of the Failure Unit

PE=M*G*DHF where DHF=change in height of the centre of mass of the failure unit

As the unit moves, the potential energy will become Kinetic Energy and Frictional Energy losses.

Kinetic Energy

KE=.5*M*V**2 where V=velocity of unit
or KE=FU*TD where TD=travel distance of unit

Frictional Energy Loss

FE=FF*TD

4. To determine the movement of the failed unit along slope and onto base.

a) Potential Energy=Kinetic Energy + Frictional Energy Losses

M*G*DHF=(FU+FF)*TD=(FG-FF+FF)*TD

Therefore:

$$TD=(M*G*DHF)/FG$$
$$=(M*G*DHF)/(M*G*\sin(TH))$$
$$=DHF/\sin(TH)$$

This equation for travel distance is only suitable while the unit is on the slope. When it travels on the flat new energy relationships occur as the Potential Energy becomes zero. Also the force of gravity in the direction of travel is zero, and

$$FF=M*G*MU$$

The Kinetic Energy of the unit is now changed to Frictional Energy Loss. Looking at the Kinetic Energy at transition, KET,

$$KET=FF*TD$$
$$TD=KET/FF=KET/M*G*MU=(1/MU-1/\tan(TH))DHF$$

This equation gives the travel distance on the flat.

2.2.5 Working Model

The working model is an application of the mathematical statements which have just been developed. It is necessary to make assumptions, at this point, that will permit the manipulation of the model, but allow the relation of reality with the numerical results. The working model utilizes the computer to allow fast consideration of a range of assumed variables. The engineering and mathematical assumptions and variables will be covered. First the assumptions will be outlined and then the selection of parameter values discussed.

1. The slope has a single angle and a discontinuity at the slope/base intersection. The slope is divided into units, each having a constant and defined depth. The length of a unit will be defined and using the slope length, N, the number of units, can be calculated. The units are numbered from the top and the section of slope which may remain will appear at the bottom and is not significant to the analysis. The model is two-dimensional.

2. The failure is of the slab-type, with rectangular units moving, although the shape of units can vary. The model does not manipulate the shape, but the centre of mass, therefore the unit can be considered as a rectangle or a trapezoid (a trapezoid can be utilized

to closer approximate a real section failure). It is necessary to calculate the coordinates of the centre of mass of each unit from the intersection of the equations discussed previously. Appendix A shows sample calculations.

3. The simple model is not dependent upon the conditions necessary for failure since failure is assumed to occur. When a unit fails, the evaluation of the movement requires that the unit move along the surface of the slope, thus by some manner the unit must be transferred to the surface. The method used is to transfer a failed unit to a position such that the height of the centre of gravity does not change [9].

4. When the unit begins to move down the slope, a frictional force acts upon it. The value of this force depends upon the angle of the slope (as the normal force is dependent upon this angle), and on the coefficients which can range in value; static, sliding, and rolling, the last two together being called kinetic. The static coefficient is active while the

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[9]A second technique was also examined. The unit was moved to a position directly above the adjacent lower unit. This method results in positive or negative changes in the potential energy, dependent upon slope dimensions. In future modeling energy increases and decreases can be identified with either an initiation energy or a loss of energy due to the failure process.

unit is not moving. Once the unit is in a state of motion, one of the other coefficients is significant. The static coefficient is the greatest, then sliding and finally the rolling. If neither the angle of the slope nor the coefficient of kinetic friction change, then any failed unit will reach the base of the slope. This inherent property of the one angle slope will be important in subsequent modeling.

5. The transition of a unit from slope to base maintaining shape is permitted by a simple, although not realistic, technique. On the base, the height of the centre of mass must not be lower than one half of its depth. Thus once the value of the height equals the suggested value during its movement along the slope, the unit is assumed to undergo an instantaneous transfer to movement along the base level.

The computer program which was designed from the above mathematics and assumptions appears in Appendix B, as the first section of the sample program. The methods of programming are not outlined in this thesis as there is a wealth of books which cover the subject (the selection of which is the individual programmer's preference). The computer program has comment cards liberally distributed throughout to explain the symbols, mathematics, and sequence of steps.

The next step is to select the input parameters of the program. To determine the values or range of values of the input, the characteristics of talus slopes are required. A partial review of related articles was given in the first chapter. The following section will discuss the input parameters and the selection of values for the Preliminary Model. Further comparisons to field studies will be made in the next chapter.

2.2.6 Input

1. Angle of Slope - Talus stands at an angle which is primarily dependent upon the material characteristics (i.e. lithology, particle size distribution, moisture and ice content), although processes of supply, movement and basal removal have an influence. Modern talus of the type in Grizzly Creek exists at angles between 25 degrees and 40 degrees, as is the case for many alpine areas (Statham (1976), Rouse, 1975). The relation of natural slope angles to the angles of repose and internal friction is a matter of controversy at present. The classical relation (Carson, 1977) is that the angle of repose and angle of internal friction are approximately equal and that they are similar to actual talus angles. This situation implies that slopes exist close to the maximum angle of stability. The newer theory (Statham, 1976) is that the angle of internal friction is approximately 5 degrees greater

than most talus angles, and that the angle of repose is not a significant measurement. The argument of this theory is that talus is formed under dynamic rockfall conditions and not a static state. Since slips are observed on modern slopes, the selection of the significant input angle from these two methods is not particularly difficult. The potential angles of failure, past and present, will be similar to modern talus angles. The purpose of this study is to examine a range of possibilities, thus the angles are assumed to permit failures and the sample values are 25, 30, 35, and 40 degrees.

The selection of slope angles is significant to the coefficient of internal friction value, since this parameter is dependent upon the angle of internal friction. It is necessary to adopt one of the theories above to select a value for the TH term of the coefficient. The simplest one to evaluate is the classical theory that the angle of a talus approximates the angle of internal friction. Within the study, the angle of internal friction and the talus angle were accepted as synonymous.

2. Slope Length and Height -- When TH is specified, then only one of slope length or height need be defined. Slope length is the distance parallel to the slope as

contrasted with the self-explanatory, horizontal length. Slope lengths vary greatly in the different alpine areas. A general range of values is from fifty metres to six hundred metres. In the Grizzly Creek area, slopes of 400 metres are standard. A range of 100, 200 and 400 metres was used for the initial model.

3. Depth of Failure - The depth of modern talus slope failures is generally a function of the active layer, anywhere from negligible depth to approximately five metres. A basic premise of this study, however, is that deep-seated failures were significant to the formation of talus derived rock glaciers. Thus, both the low range and greater depths must be considered. Consequently, values of two, five, fifteen and twenty-five metres were used as sample figures. A secondary reason for using the twenty-five metre depth is that the toes of rock glaciers in the Grizzly Creek area are approximately this height.

4. Failure Unit Length - The value of the failure unit length is tied to the value of slope length and the number of units. Any two will determine the third. Again using the rock glaciers of the Grizzly Creek area as a basis, the unit length can be related to the width of the lobes as one extreme. One mode attempts

to explain the lobes by successive failures of units. If there is a single failure of the whole slope, or if compression of the lobes occurs, then other values of unit length are significant, so a range of values will be examined. The value used was related to slope length and ten, twenty, forty and one hundred metres were the values tested.

5. Coefficient of Friction - The value of this parameter is the most difficult to set, yet the most important to the study. Gerber and Scheidegger (1974) use a factor of tan(TH) to determine the different coefficients of friction. Since the coefficient of internal friction is the tangent of the angle of internal friction, this technique is utilized also. If the failed unit is sliding along the surface then a value of tan(TH) will cause an immediate stop upon failure, unless initial energy has been provided to the unit (which is the argument by Gerber and Scheidegger). Failures occur in slopes such that normally no energy is transferred to the unit, therefore, for a unit to continue movement the coefficient of friction must be less than tan(TH), and in that case the section will reach the base on a one angle slope. For the purpose of initial modeling, the values 0.5*tan(TH), 0.7*tan(TH) and 0.9*tan(TH) were used. The value 0.9*tan(TH) is suitable for the sliding mechanism. A

second possible type of movement is that the lower layers of the unit are rolling, thus the coefficient of friction will be lower. One further type of movement could be an air or liquid lubrication (due to melt of ice upon failure) which will also provide a low value for the coefficient of friction. The values 0.5*tan(TH) and 0.8*tan(TH) are an attempt to consider these latter postulated mechanisms of movement (the multipliers, 0.5, 0.7, etc. will be termed the factor of the coefficient of friction, FMU).

The output of the Preliminary Model provides the time of movement, TS, and the value of the extension from the talus/base intersection. The results of the input variation are tabled and discussed in the next chapter. The construction of the Interaction Models is the next step in the modeling of rock glaciers.

2.3 INTERACTION MODEL

The simple deterministic model has been constructed as the preliminary step in a dynamic approach to the modeling of rock glaciers. A wide variety of feasible parametric values were utilized in the initial model to examine their effects in isolated situations. The movements of the complete talus slope or individual sections of the talus were examined in a non-interactive process. In the actual case of a talus failure, particularly a retrogressive collapse, sections of the slope will interact during a downslope movement. The next step will be to construct an interaction model, within which a number of postulated processes can be active in forming the features of a rock glacier.

The results of the Preliminary Model are discussed in the next chapter, however they will be incorporated within the interaction model. Within this Methodology chapter, the more complex model will be constructed, and the contributions of the initial model will be discussed. In hypothesizing potentially active processes, a short discussion will outline their theoretical possibilities. A more complete evaluation of the different models and their results will follow in the next chapter. Through the dynamic feedback aspect each subsequent alteration of the interaction model will incorporate results of earlier models.

As for the initial deterministic model, the construction of the basic interaction model will follow a step by step procedure. The development will be outlined, with the basic mathematical and physical theory. For a more complete theoretical explanation, Appendix B illustrates the mathematical steps and construction of the computer program.

2.3.1 Conceptual Model

A talus slope as per the Preliminary Model exists. Failure will occur, with a significant portion of the slope being involved in the avalanche, In the case where a retrogressive failure occurs, the slope sections can interact through collisions during their movement down the slope. The types of interactions will be postulated after the basic model has been developed. Again the movement will be considered as a dry friction type.

2.3.2 Word Description

The slope of angle, TH, is described on a two-dimensional X-Y axis. The various parameters will be defined or calculable as per the Preliminary Model (i.e. slope length, height, etc.). The extent of failure will be defined and the times of the initiation of unit movements will also be defined to allow the determination of interactions. Interactions will be described as collisions which can vary from inelastic to elastic. The failures will again follow the laws of physical dynamics. The active forces are gravity and friction and the section will move along the slope and possibly on to the horizontal base.

2.3.3 Discrete Word Statements

1. The slope exists at an angle, TH, with a related height and length. The x-axis is the base of the slope and the y-axis equivalent to the headwall.

2. The extent of a failure will be defined by the number of failure units and their locations. The units are defined by their width and depth and will be considered as rectangular. The units will maintain their shape, although subsequent modeling may change this assumption.

3. The initiation of movement of each unit will be defined on a scale of time.

4. Each section moves downslope under the influence of gravitational and frictional forces. Due to collisions, (inelastic and elastic), there may also be interactive forces.

5. The movement includes the part along the slope, with a possible extension onto the base.

2.3.4 Discrete Mathematical Statements

The basic equations defining position and outlining energy considerations were discussed under this heading in the development of the initial model and will not be repeated. The step by step construction of the interaction mathematics will be outlined. Appendix B covers the detailed theory.

The characteristics of the slope and failure sections have been described, therefore the discrete statements will be laid out for the word statements starting from 3.) above.

1. In an avalanche of NF units, the first will start at time, t=0. Each subsequent unit failure will have an initiation time defined by a factor of a parameter which is the time interval between successive unit failures, TI. As an example if the units are labeled from I=1 to I=NF and they fail starting with unit NF then, the failure time of the Ith unit is

FT(I)=(NF-I)*TI

If unit #1 is the first to fail then

FT(I)=(I-1)*TI

2. The active forces are friction and gravity, however as the model is developed, forces of interaction (which are based on friction and gravity) may alter the usual influence of these two forces. To determine the effect of these interactions, units that fail can undergo a process which will be called a collision. Upon collision, movement characteristics can change and will be determined from assumptions made for each type of interaction. Before examining collisions, their occurrence must be calculated. A collision is assumed to occur when one unit's front edge meets the rear edge of another unit. Since movement is referenced to the centres of mass, the situation occurs

when the centres are one width, W, apart. To simplify calculations a variable termed the position, POSN, is used. POSN is defined as the x component of the coordinates of the centre of mass. Therefore collision on the slope will occur between unit I and I-1 when

POSN(I)-POSN(I-1)=W*cos(TH)

and on the base when:

POSN(I)-POSN(I-1)=W

From the equations for POSN, the times of interaction between the units can be determined. As each collision occurs the variable values change, increasing the complexity of calculations, however the simple defining relationship above still determines an interaction (Refer to Appendix B for the mathematical manipulations).

After the occurrence of a collision has been determined, the effect of the interaction must be defined. The next section outlines the construction of models which attempt to produce forms similar to rock glaciers. Each modification of the Interaction Model will incorporate a hypothesis of flow mechanisms, to examine a possible role in the formation of a rock glacier. The results are tabled and discussed in the next chapter. Each subsequent model includes improvements in input or mathematical manipulations which develop from earlier results.

3. Movement

When failure has occurred, the segment of talus will move downslope under the influence of gravity and friction. The postulate of this thesis is that a talus failure will be retrogressive. The movement of this complex failure may produce features similar to a rock glacier. To model the movement of the slope, a number of mechanisms are proposed to describe the interaction between the sequence of collapses. The results of each hypothesis will be examined in the next chapter to identify any characteristics of rock glaciers which may be produced.

2.4 ELASTIC MODEL

The first proposal is an interaction by elastic collisions between each failed unit of slope. The units are defined as equal in size and they maintain their shape throughout the movement. An elastic collision results in a conservation of momentum, such that the units exchange velocities and there is no loss of energy through heat absorption (change in shape). By this mechanism the energy of upper units is transferred to the lower units. The result is that the lower units extend the farthest onto the horizontal base, the reverse of the Preliminary Model results.

For the case of an elastic collision between units I and (I-1), the initial velocities can be calculated from equations developed in the appendices. The final velocities will be:

VAC(I)=VATC(I-1)	VAC=velocity after collision
VAC(I-1)=VATC(I)	VATC=velocity at collision

With the change in velocities the movement parameters of the complex elastic flow change. A new set of conditions are developed and the next collision calculated. This procedure is iterated until a maximum number of units have moved on to the horizontal base. The number of iterations is dependent upon the defined input values, as is the quantity of units which move off of the talus slope. The input to the Elastic Model is now considered.

Since the Elastic Model is the initial collision hypothesis, the first series of manipulations examined a variation of parameters on the same scale as for the preliminary case. Elastic collisions showed little sensitivity to changes in most variables, consequently significant variations of input parameters were limited to a few variables. The results of the Preliminary Model (discussed in Chapter Three) also aided in the selection of input parameters, by allowing early elimination of some extremes.

TH was ranged between 25 and 40 degrees, and the final forms of the movement were found to differ only slightly. TH was subsequently examined only peripherally, as other parameters were varied, to ensure that there was no interdependency. The dimension measurements, such as depth, D, and slope length, L, fell under a similar classification in that there was little effect on the interaction mechanism, or the final form.

The important input parameter was FMU, as it affected the energy of the moving units. FMU was examined at 0.5, 0.7, 0.8, and 0.9. NF and TI were ranged from 5 to 15 units, and 0.5 to 2.0 seconds respectively, although the results were not as significant as for those of FMU variation.

The Elastic Model produces a set of coordinates of the centres of mass of the failed units along with their time of travel and extension, EXT, from the slope.

The results of the variations are discussed and tabled in Chapter Three under the Elastic Model. The next step is the modification of the collision process to consider a mechanism which is not perfectly elastic.

2.5 OVERRIDE MODEL

The Override Model incorporates a modification which assumes that upon cessation of movement, a unit will not be involved in any subsequent interactions. When a unit is moving, the occurrence of a collision which permits an exchange of energy is feasible, however when the section has stopped, a trailing unit will probably override (considering a dry friction movement). Since an actual talus section will not maintain its shape indefinitely, the mechanism acts such that when a unit has stopped, trailing sections will move as if the original surface conditions have not been altered, or as if the stopped unit has dispersed itself. The process will be discussed further after the results are listed.

The input is similar to that utilized in the Elastic Model. The major change is that the final forms are especially dependent on FMU and D. The values of FMU were varied from 0.7 to 0.9 and D was given the values 5, 15 and 25 metres. The other parameters were examined within the framework of the FMU and D influences.

The output gives values for the time of movement and the extension from the base. Diagrams and tables describe the results in Chapter Three. This modification requires only slight changes in the Elastic Model, so there is no new mathematical assumptions. The next modification moves completely away from elastic collisions and utilizes overriding processes exclusively.

2.6 HITCH MODEL

The hitch mechanism assumes that a unit which is overriding a moving unit will absorb some energy from the lower section. The result of the override is that the lower unit will slow down faster due to the extra mass (thus increased normal force), and the upper unit will move farther because it is moving on material which already has a velocity; thus the exchange of energy. If a unit has stopped, the movement of subsequent sections will occur by the mechanism of the Override Model, or no interaction with stopped units. The feasibility of the modification is discussed in Chapter Three.

The Hitch Model results are influenced primarily by FMU variation and to a lesser degree by changes in TI. FMU was ranged from 0.9 to 0.7 and TI was varied from 0.5 to 1 second. The other parameters were examined for significant effects within the FMU and TI variations.

The output of the Hitch Model is similar to the Override and Elastic Models. The time of movement and extension from the base of the talus are produced. The results are tabled and examined in the next chapter. The remaining topic to consider in this initial modeling methodology is the technique of analyzing the results of the model manipulations.

2.7 ANALYSIS TECHNIQUES

The results of the models provide the coordinates of the centres of mass of units which have moved on to the horizontal base. One of the initial assumptions is that a unit maintains its shape throughout a flow. The Hitch and Override mechanisms require a partial suspension of this assumption to make overrides feasible. An actual talus flow of a non-cohesive section will probably spread over the length of its movement. A cohesive unit (or a unit which acts cohesively) will maintain a greater bulk of its original mass. The methods of analyzing the results of flows consider ideal cases of both cohesive and non-cohesive units. Three techniques were utilized. Each will be briefly outlined, with their feasibility within the framework of rock glacier evolution discussed later in Chapter Three.

The first method assumes that a unit maintains its complete mass during a flow. Where units overlap the height of the surface will be the sum of the depths of the constituent units. This technique results in abrupt changes in surface height with vertical slopes between each height.

The second technique, termed the strip method, postulates a process which results in the dispersal of material during the flow of a section. As a unit moves down the slope and along the base, the lower surface is acted upon by friction. The friction can either be sliding or rolling of material along the interface. The strip technique assumes that material is stripped from the lower layer of the unit due to the frictional force. The rate of loss is set at either 0.5 or 1 metre for every width (W) of travel distance (the rate is determined by the initial depth; the technique is not used for D=5metres). The resultant forms are similar to those analyzed by the first method, although they do not exhibit the same extremes.

The third method is actually a modification used within the first two analyses. Since a failed unit will probably form an extended shape, the fringes of a unit will not be as high as the peak location. By halving the width of a stopped unit the extent of a section's final mass is decreased and the extended shape is approximated. This method is used to modify final forms resulting from the first two techniques.

The analysis techniques result in features which have vertical changes in height. The results are illustrated in the figures of the next chapter. No attempt is made to approximate a gentle contour of the form surface, as such an interpolation would surpass the significance of the flow and analysis techniques. The identification of rock glacier characteristics from the figures is discussed in Chapter Three (The evaluation of the analyses is also included).

Chapter III

RESULTS AND ANALYSIS

The development of a mathematical flow model required the simplification of the field situation to study specific aspects. In this research an attempt to describe a process which may not be currently active further compounded the detached nature of the study. To return the research to a valid field application, a range of parametric values was employed, in conjunction with a number of hypotheses of possible mechanisms. A sizable collection of data was created, which required sifting to identify significant results.

These results are compiled in tables and illustrated in diagrams throughout the chapter. Each model is discussed as to the significance of the results, and its feasibility with consideration of the assumptions. The overall discussion of the catastrophic process as it applies to rock glaciers, follows in the final chapter.

3.1 PRELIMINARY MODEL RESULTS

Variation of parameters within the Preliminary Model allowed the observation of the effects of different conditions upon the

L = 400 metres W = 20 metres D = 5 metres N = 20 FMU = 0.8

Unit / Angle (°)	EXTENSION (metres) / STOP TIME (seconds)									
	1	2	3	4	5	6	7	8	9	10
25	85 / 37	81 / 36	76 / 35	72 / 34	67 / 33	63 / 32	58 / 31	54 / 29	49 / 28	44 / 27
30	82 / 34	77 / 33	73 / 32	69 / 31	64 / 30	60 / 29	56 / 28	51 / 27	47 / 26	43 / 24
35	78 / 31	73 / 30	69 / 30	65 / 29	61 / 28	57 / 27	53 / 26	49 / 25	45 / 24	41 / 23
40	73 / 29	69 / 28	65 / 28	61 / 27	57 / 26	53 / 25	50 / 24	46 / 23	42 / 22	38 / 21

Figure 13: Preliminary Model TH Variation

L = 400 metres   W = 20 metres   N = 20   FMU = 0.9   TH = 35

Unit / Depth (m.)	EXTENSION (metres)				
	1	2	3	4	5
2	35	33	31	30	28
5	34	33	31	29	27
10	33	32	30	28	26
25	30	28	27	25	23

Figure 14: Preliminary Model D Variation

movement of a talus failure. The isolation of trends aided in simplifying the manipulation of subsequent, more complex models. The results from the Preliminary Model are listed in tables and will be referred to frequently in the following analysis.

3.1.1 Variation of TH

Within the Methodology Chapter, the importance of TH was discussed. TH is not simply a parameter indicating slope dimensions, but it also inherently, is a measure of the characteristics of the constituent material. This second aspect is a result of the assumption that the model slopes exist at potentially unstable angles. These angles are a result of two aspects :

1. micro and macro factors of slope condition

2. the characteristics of the material

Within this simple model, the slope angle is directly related to the angle of internal friction which is dependent upon the material characteristics, therefore a change in angle , TH, is associated with a change in coefficient of friction (which is defined as a function of TH). Examination of the effects of varying TH highlight this factor.

Keeping slope length, L, constant, TH was varied from 25 to 40 degrees at 5 degree increments. In Figure # 13, typical results are shown for the defined values. As TH increases, the units take less time to stop after failure, however they do not extend as far from the base of the slope. Since a higher angle implies a higher potential energy for a unit the results at first appear to be reversed. From the discussion above, a change in TH can be seen to cause a change in the coefficient of friction, which has a greater effect on the movement of a unit[10].

Example 1	TH= 35 degrees		
	Unit 6	YAF= 162 metres	EXT= 57 metres
	TH= 25 degrees		
	Unit 1	YAF= 162 metres	EXT= 85 metres
Example 2	TH= 35 degrees		
	Unit 15	YAF= 59 metres	EXT= 20 metres
	TH= 25 degrees		
	Unit 13	YAF= 60 metres	EXT= 30 metres

Due to the effect of the lower MU, when two units start from the same height, the unit on the lower angle slope will move farther along the base. When slope length remains constant, the other slope dimensions of height, H, and horizontal length, HL, vary with TH. Increasing a unit height, on a higher angle slope will compensate for the effect of lower angles. Thus, Unit 9 at TH=35 degrees, YAF=128 metres, moves about the same distance as

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[10]The time of movement is not an important parameter to the Preliminary Model, but the results of the interaction models are affected by the time factor, so its changes are noted.

Unit 10 at TH=25 degrees, YAF=85 metres (45 and 44 metres respectively). When the depth is increased to 25 metres, the height difference for equidistant movement decreases slightly (for D=5 metres, about 50% height difference required, for D=25 metres about 35% difference). Increasing the height is equivalent to increasing the horizontal length of the slope.

3.1.2 Variation of D

The depth variation was referred to above as it relates to TH. The depth values tested ranged between 2 and 25 metres. The lower value is an approximate depth of the active layer on alpine talus slopes. The upper value relates to the depth of rock glaciers present in the Grizzly Creek area of the Yukon. Changing the value of D does not significantly affect the output of the Preliminary Model. The depth which is used, is significant to the postulated mode of formation of the rock glacier, which will be discussed in the modified models. A deeper failure plane results in a slight decrease in potential energy of a unit, since the lowest the centre of gravity can move to is one half of the depth[11].

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[11]This result can be observed in Figure-# 14, where the value of EXT decreases slightly as the depth increases. The effect also explains the change in percentage height differences between D=5 and D=25 metres required to compensate for TH variation (as discussed above).

3.1.3 Variation of MU

The coefficient of kinetic friction is dependent upon the characteristics of the talus material and the mechanism of movement of a unit. MU is defined as a factor, FMU, less than unity, of the tangent of TH. If MU is equal to tan(TH), then movement cannot occur unless the failure has an initial energy. The variation of FMU is an examination of the range between no movement or maximum friction, and ideal movement or no friction.

Studying the results in Figure # 15 of varying FMU, from 0.9 to 0.5, the effect on EXT is quite significant. A flow at FMU=0.8 results in a value of EXT more than double that of the 0.9 value. Further decreases to 0.7 and 0.5 cause increases of more than three and nine times respectively. The selection of an appropriate value for FMU depends on three aspects :

1. the mechanism of movement - whether the unit is sliding on the surface, or the lower layers are rolling.

2. the interaction between sliding talus debris and the static talus surface.

3. the presence of a lubricant such as water or air.

None of these aspects have been accurately evaluated. Gerber and Scheidegger (1974) estimate FMU values from the first two aspects for modern small scale processes of catastrophic

L = 400 metres W = 20 metres N = 20 D = 25 metres TH = 35

Unit / FMU	EXTENSION (metres)									
	1	2	3	4	5	11	12	13	14	15
0.9	30	28	27	25	23	12	10	8	6	4
0.8	68	64	60	56	52	27	23	19	15	11
0.5	273	256	240	224	207	109	92	76	60	43

Figure 15: Preliminary Model FMU Variation

L = 400 metres D = 25 metres FMU = 0.8 TH = 35

Unit W (m.)	EXTENSION (metres)									
	1	2	3	4	5	11	12	13	14	15
400	29									
40	66	58	50	42	33					
20	68	64	60	56	52	27	23	19	15	11
10	69	67	65	63	61	49	47	45	43	41

Note : N changes with W when L remains constant.

Figure 16: Preliminary Model W Variation

movement. Their process-restricted values are not appropriate to the avalanche process which has been suggested. The model values are utilized to consider not just the variation between static friction and kinetic friction but a further differentiation to a sliding kinetic friction and a rolling kinetic friction, and also the possibility of lubrication. The lower the value of FMU, the greater the influence of one or a combination of the three aspects, to decrease frictional energy losses. Further modeling will incorporate the full range of FMU values to develop rock glacier features.

3.1.4 Variation of W and N

Variations of W and N are closely linked in the Preliminary Model, especially if the slope length remains constant. In Figure # 16, the effects of leaving L=400 metres and changing W from a low of 10 metres to a high of 400 metres can be observed. The separation of the units doubles with a twofold increase in W as expected. The movement of the units is still dependent upon the height and slope angle. In the Preliminary Model the width variation within the lower range is insignificant.

When W=400 metres and N and NF are 1, the model causes a movement of the centre of mass of the unit to a position where EXT=29 metres. This value implies that the front edge of the failure would be located at a distance of 229 metres from the base of the slope. Changing of the width value affects the validity of the transition assumption. The transition assumption requires the centre of mass to accelerate down the slope until XTR is reached. When W is small the assumption is suitable, but when the front edge of a unit has moved onto the base 200 metres before the centre of mass, then either the unit must slow down or else it will change shape. In each case the present model does not permit this consideration. Thus for a large scale failure which is not retrogressive, a different modeling procedure would be required. Lower W values (i.e. below 40 metres) are valid for the subsequent modeling[12].

The results of the Preliminary Model permit initial examination of the proposed avalanche mechanism. The output allows the streamlining of input parameters for subsequent work. Understanding of the basic characteristics of the model flow contributed to the formulation of the interaction models, the results of which follow.

3.2 ELASTIC MODEL RESULTS

The Elastic Model assumes a retrogressive failure of a slope with elastic collisions occurring between units during the sub-

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[12] An interesting result of setting N=1, L=400 metres and varying TH from 35 to 25 degrees is that the movement of the centre of gravity is almost equal, EXT=29 and 30 metres respectively. Thus this model would imply that large scale avalanches on similar dimensioned slopes with different constituent materials will produce similar features.

sequent flow. An elastic interaction causes an exchange of velocities and results in the units maintaining their order during movement. Thus the lowest or earliest moving units will extend the farthest from the end of the slope. This section tables the results of the model manipulations. The feasibility of the model and its relation to rock glaciers will be discussed following the results of the other interaction assumptions.

The construction of the model was outlined in Chapter 2 and Appendix B. The elastic collision process causes the lowest units to move the farthest. The values of EXT do not increase as YAF decreases, as expected, until after Unit 5. This contradiction occurs because of the limitations of the mathematical operation of the model. As more units move on to the base, the separation between the slope units becomes less and there is a 'crowding'. The time difference between collisions becomes small (less than 0.5 seconds) so that the movement of all units on to the base requires a large number of iterations (over 175). In reality, this situation is not feasible, therefore the number of iterations was limited (maximum 75) so that the units that moved on to the base did so without the occurrence of a backup situation.

Each data table indicates the units which moved on to the base and the total number of units failed. The other units are presumed to have stopped on the slope, with no assumption of their final form.

The variations of parametric values have an interdependent influence on the output. The effect of changes in TH, FMU, or D must be examined with reference to changes in the other two. The output is relatively insensitive to variations in TI and NF. The Elastic Model is dependent upon the total energy activated during failure and not on the time factor. Any alteration of the height of failure units (such as changing D or L) will be reflected in the results.

Variation of TH affected the values of EXT for different units, but neither the separation of the units nor the number which moved onto the base changed significantly, even with variation of other parameters. The EXT of the units was greater, the lower the value of TH as shown in Figure # 17 (as for the Preliminary Model also). Again this is due to the related lowering of MU.

As FMU varied so did EXT, to a greater degree than with TH changes. The lower the value of FMU, the higher the values of EXT for units. There also is a decrease in separation between the units, because there are more moving onto the base. Figure # 18 shows a sample table for FMU comparisons.

Changing D, NF, or L is an indirect method of altering the height of the failure sections. A greater height gives greater potential energy to the system, thus EXT values increase. Lower

FMU = 0.8 D = 25 metres TI = 1 second W = 20 metres L = 400 metres

	EXTENSION (metres)									
TH (°) \ Unit	1	2	3	4	5	6	7	8	9	10
35				1	18	42	63	87	108	149
25				1	24	46	67	90	112	155

Figure 17: Elastic Model TH Variation

D = 25 metres   TI = 1 second   TH = 35   W = 20 metres   L = 400 metres

	EXTENSION (metres)									
Unit / FMU	1	2	3	4	5	6	7	8	9	10
0.9						1	12	35	57	79
0.8				1	18	42	63	87	108	149
0.7		1	16	39	60	82	103	149	179	216

Figure 18: Elastic Model FMU Variation

FMU = 0.8 TI = 1 second TH = 25 W = 20 metres L = 400 metres

	EXTENSION (metres)									
Unit / D (m.)	1	2	3	4	5	6	7	8	9	10
5			4	19	40	61	83	119	146	167
25				1	24	46	67	90	112	155

Figure 19: Elastic Model D Variation

D = 25 metres TI = 2 seconds. TH = 35 W = 20 metres L = 600 met

Unit	1	2	3	4	5	6	7	8
Extension (metres)					6	7	12	35
Unit	9	10	11	12	13	14	15	
Extension (metres)	64	96	121	150	183	213	244	

Figure 20: Elastic Model L Variation

D = 5 metres   TI = 1 second   TH = 35   W = 20 metres   L = 400 metres

	EXTENSION (METRES)									
Unit / FMU	1	2	3	4	5	6	7	8	9	10
0.9	15	11	53	7	49	4	45	1	41	38
0.7	79	126	173	31	78	125	172	30	77	124

Note : The increase in FMU causes much greater extension, and also affects the order.

Figure 21: Override Model FMU Variation

D = 25 metres   TI = 1 second   TH = 25   W = 20 metres   L = 400 metres

	EXTENSION (metres)									
Unit / FMU	1	2	3	4	5	6	7	8	9	10
0.7	149	97	127	84	109	71	91	58	71	45
0.8	79	68	64	59	55	50	46	40	38	28

Note : At 0.8, a simple reverse order flow results, but for 0.7 the Hitch mechanism causes a variation in the final order.

Figure 22: Hitch Model FMU Variation

values of D increase YAF (since the centre of mass is only D/2 under the slope surface) as does longer L. Another effect of lowering D can be observed in Figure # 19. One more unit has moved on to the base at a depth of 5 metres.

By increasing NF to 15 at the set value L=400 metres, the lower units N=11 to 15 are included in the flow. The results are similar to NF=10, with no more units appearing on the slope. When the L is increased, the potential energy of the system increases and can lead to more complete flows as shown in Figure # 20. Changes in W did not produce significantly different results.

Finally, the effect of TI is negligible. This state arises due to the dependency of the Elastic Model on the potential energy activated and not the time aspect of flow.

Within this interaction model, the initial assumption is that the sections can collide elastically and then continue movement. The forms produced by the flows are similar in that the units maintain their failure order. The effects of analyzing the results by different techniques will be compared to the other models after their results are considered.

3.3 OVERRIDE MODEL RESULTS

The Override Model permits elastic collisions between moving units, but results in an override by subsequent units upon the stoppage of a unit. This process causes varying sequences of unit positions after a flow, dependent upon the energy transfer from upper units to the lower units. Since this simple model assumes that the override mechanism does not absorb energy, the trailing units move to their maximum potential (if there are no more elastic collisions).

There are few significant trends which appear with the variation of single parametric values. Instead, a range of features are produced from an interdependency between different variables. The most significant variables are FMU and D as they are the major determinants of the separation between units and the size of the resultant features.

D and FMU provide the basic influences on the final positions of the failed units. Within their variation, TH and TI also have significance. Unlike the Elastic Model, the Override Model is dependent upon the time of flow as well as the energy of the system. Depth is utilized as the prime factor and FMU is then examined at the different values of TH and TI, within the D framework.

D is examined for the values 5, 10, and 25 metres. FMU determined the separation of the units and the extension of the feature, and in conjunction with TH and TI, the order of the stopped units. At all values of D, the lower the coefficient of friction, the greater the movement of units, and consequently their separation. Figure # 21 illustrates this effect. The basic result is the same for TH=25 degrees. Units appear in groups (centres of mass clustering) of two or more when TH=35 degrees for different values of D and FMU, but the grouping trend is not as strong for TH=25 degrees. The variation of TH results in greater extension for lower values of TH, at all values of D and FMU. When TI varies from 0.5 to 1 second there is no consistent difference in the final unit positions, however when TI=2 seconds, the units are usually in reverse order (highest moving farthest), because fewer elastic collisions occur. The result is greater clumping or less separation between units.

These results can be observed in the analyses which are discussed later. The comparisons to rock glacier forms and characteristics and the feasibility of the model will be considered in the general discussion following the Hitch Model results.

3.4 HITCH RESULTS

The Hitch Model incorporates a second assumption for an override mechanism. When a unit is still moving, rather than colliding elastically, a trailing unit will override. The front unit will halt sooner and the encroaching unit will increase its travel distance. The override mechanism will continue until all of the units have ceased to move. Upon encountering a stopped unit, subsequent units will continue movement with no influence from the stopped section.

The prime variable controlling the output of the hitch process is FMU. At the values FMU=0.9 and 0.8, all variations of TH, TI, NF, and size dimension of units result in similar outputs, with only slight difference in separation of the units and the usual change in EXT. The separation is most consistent at TI=1.0 with usually not greater than 10 metres of distance between the final positions of the units (which generally are in a reverse order from their preflow positions, i.e. EXT(10)<EXT(9)<etc.)

At FMU=0.7, the additional energy gained by an overriding unit, becomes significantly influential to cause an unordered arrangement of the units after flow as displayed in Figure # 22. Results of the Hitch runs at FMU=0.7 with the form analyses are discussed in the next section.

3.5 ANALYSIS

Four models of the movement of a failure were developed to identify any similarity to rock glacier features. The effects of varying the input parameters of each, were outlined in the previous section. The results of these models define the centres of mass of units which have moved under the respective mechanisms. This section will evaluate each model by :

1. analyzing outputs using several techniques

2. comparing these results to actual rock glaciers

3. and finally by considering the feasibility of each set of assumptions

This objective analysis is the final active step in the dynamic process of modeling.

Before the models are evaluated, the characteristics of the Grizzly Creek area talus derived rock glaciers will be outlined, for subsequent comparisons. The chosen rock glaciers have been studied over a period of five years (P.G. Johnson, 1974, 1976, 1978) and it was the problems of their interpretation which led to the initiation of the present study. Consequently their characteristics will be used for the evaluation of the models.

Figures # 3, 4, and 5 show the profiles of two talus derived rock glaciers and an avalanche rock glacier (terminology - P.G. Johnson). Assuming a single angle as per the model, by extending the talus slope to the base, the farthest extension of mate-

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[13] The talus derived rock glaciers have experienced some basal removal, so maximum extension may be up to 50 metres greater.

rial is between 100 and 200 metres[13]. The depth of the rock glaciers averages 20 metres at the toe. The number of ridges differs on the two talus derived types, the larger one (Northern Rock Glacier) having a greater number (more than 15). The Northern Rock Glacier lobes are compressed in some areas and dispersed in others. They vary in width (longitudinal length) from 5 metres to 20 metres and in height (amplitude) from 5 to 15 metres. (The total depth to the valley floor is still over 20 metres, measured by tracing valley form.) The talus slopes in the area are between 30 and 35 degrees, and the original slope lengths are difficult to determine, but are greater than 200 metres. The talus slopes in the Duke Talus Glacier are over 400 metres. These characteristics will be used for comparisons to the modeling results.

The Preliminary Model was a non-interactive type. The movement of each unit was calculated as if it had been an isolated flow. The purpose was to evaluate the influence of the variation of a range of input parameters (covered earlier). In a retrogressive failure of a talus, a non-interactive flow could result in features similar to those in Figures # 23 and 24. In such a flow the units would override and by definition, an override would not affect the movement of either unit. Consequently the centres of mass would be separated by the distances which the Preliminary Model produced (determined by the value of the input parameters). Figure # 23 illustrates the results which occur for high values of the coefficient of friction. There is small separation between successive units, and the extension from the slope is also small. The feature is one large mass by all of the analysis techniques.

At the lower value for FMU (0.5) the units can move farther, thus the separation and extension increase, resulting in features which display a ridge sequence. The model produces a lobed form which is dependent upon several assumptions :

1. retrogressive failure

2. single angle slope

3. definition of values for input parameters, such as FMU=0.5

4. analysis methods (flow characteristics)

5. non-interaction

The first four assumptions are common to all of the models and will be discussed later. The last assumption is specific to the Preliminary Model.

As a model section of slope moves on to the horizontal base, it will create a feature which should influence the subsequent units. The slope may be lessened near the base, or an obstacle

FIGURE 23

PRELIMINARY MODEL I

TH=25°
D=15 m.
FMU=0.7

ANALYSIS 2/3

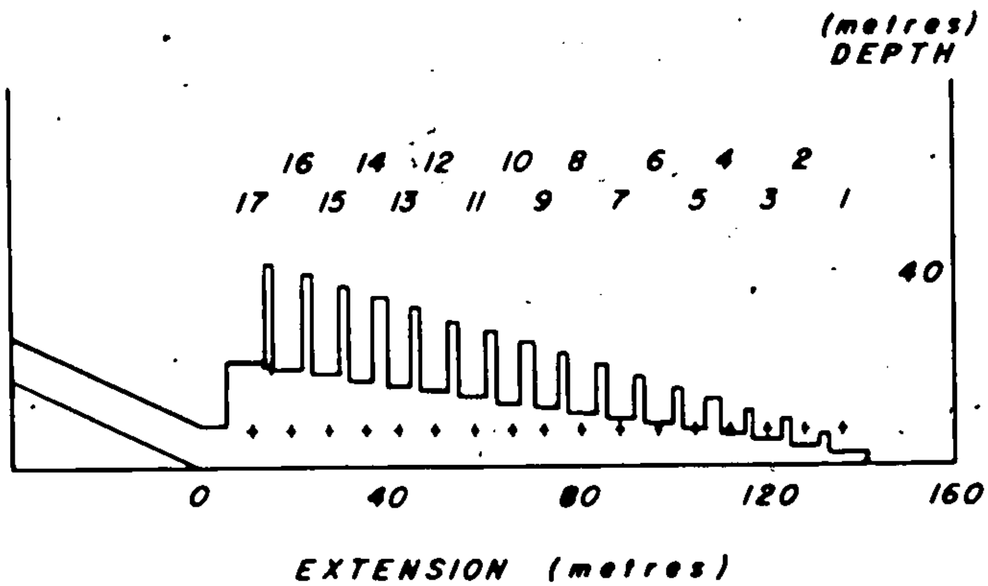


FIGURE 24

PRELIMINARY MODEL II

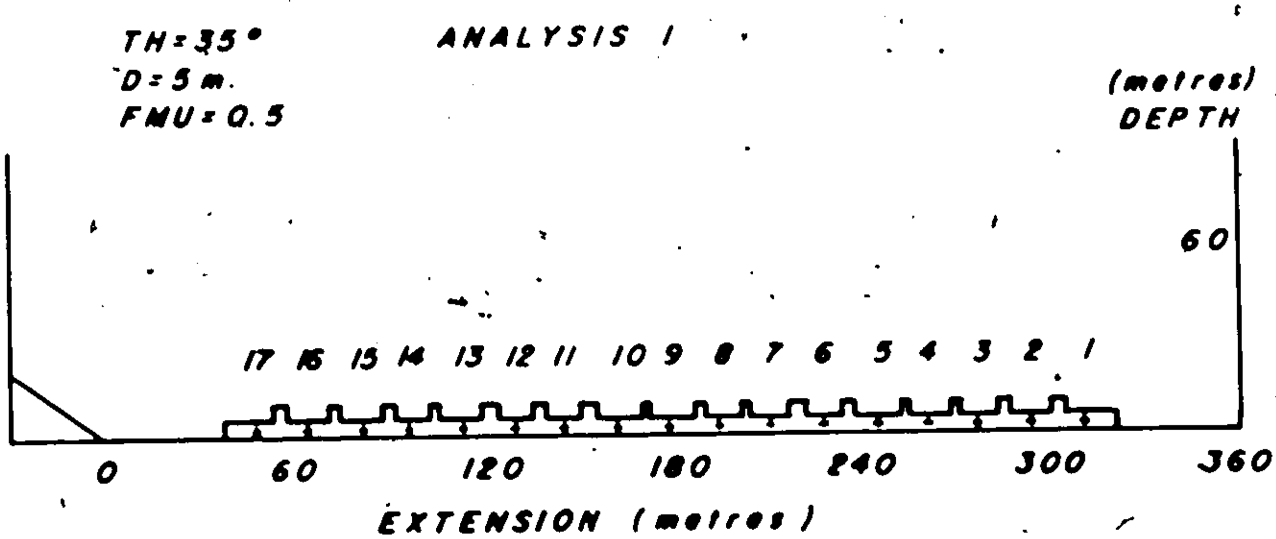


FIGURE 25 — ELASTIC MODEL I

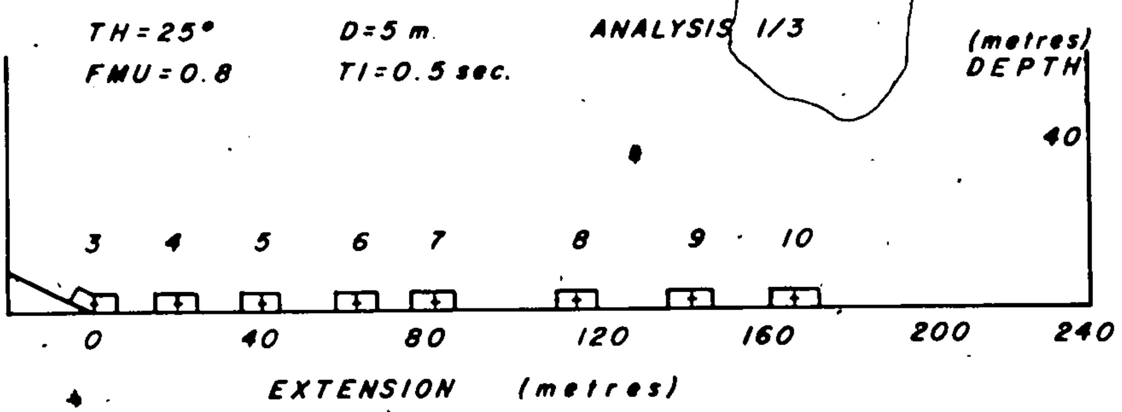


FIGURE 26 — ELASTIC MODEL II

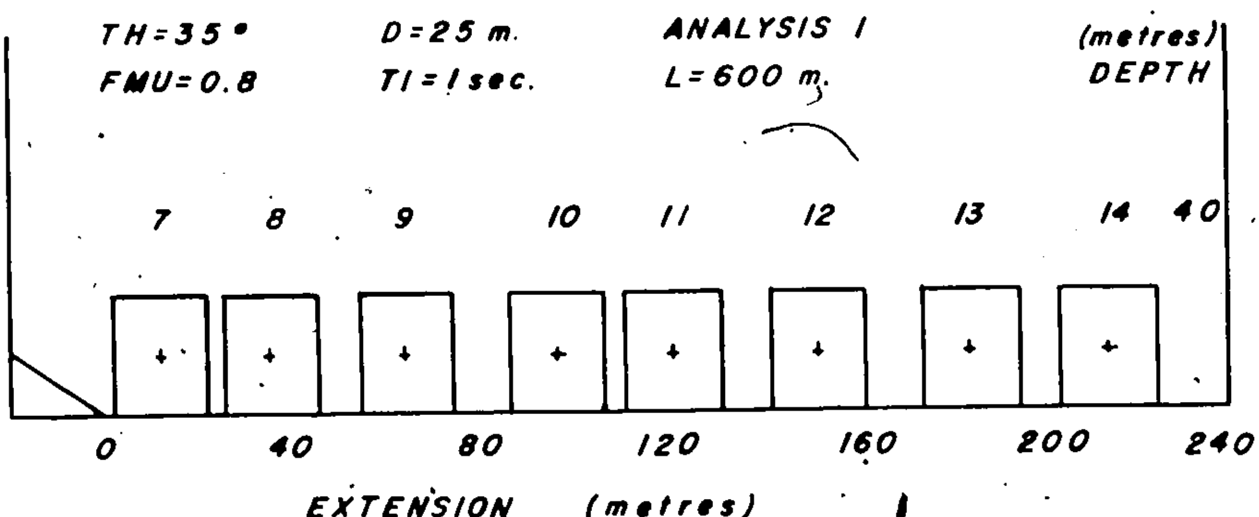
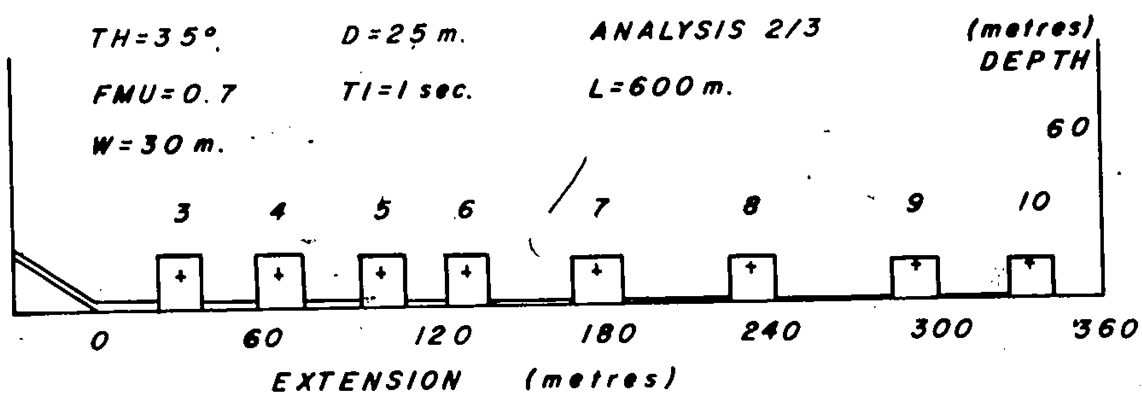


FIGURE 27 — ELASTIC MODEL III



may be created which will either slow down the trailing section or cause an exchange of energy. The analyses illustrated (Figures # 23 and 24) assume that no interactions take place. Subsequent models are an attempt to incorporate interaction processes between the failed units. The first of these designs is the Elastic Model.

A range of features can be created by the combination of the variation of input values in the Elastic Model, and the method of analysis of the results. Typical forms are illustrated in Figures # 25 to 27. The units involved in an elastic collision type of movement are separated from each other by a distance greater than their width (with occasional exceptions), at all input values. Thus there is no significant amalgamation of units which have moved on to the base[14]. The extension on to the base is dependent upon the input parameters and can be varied over a large range. At FMU=0.7, the maximum values of extension, 250 metres, in the Grizzly Creek area can be obtained. The depth of the features is determined by the input parameter D. With the assumption that a unit maintains its shape, the depth is equal to D, but by the strip method, the feature's depth decreases with extension. To maintain a depth of 20 metres at the toe a large (above 20 metres) input value for D would be required.

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[14]On the talus slope, those units which have not moved on to the base are assumed to have stopped, but their form is not considered in the analysis.

The number of units on the flat determines the number of lobes created. This value was mainly dependent upon FMU and NF (in conjunction with L) and it can be varied easily. The consequence of higher NF is that there is a crowding of units on the slope, which is not readily identifiable in the field situation. The slope length was varied from 200 to 600 metres, with better results for longer slopes. The best results with respect to W, occurred for W=20 metres[15].

In referring to the 'best' results, these occur when the maximum number of units move on to the slope and the construction of form produces a series of ridges out to a suitable maximum extension. A series of ridges are formed by all sets of the input, but the number varies. At FMU=0.9, only 5 or 6 lobes can be formed and the extension is less than 100 metres (independent of other parameters). The extension at FMU=0.8 reaches between 150 and 200 metres, and allows 8 or 9 lobes to form. When FMU is decreased to 0.7, the feature moves out over 200 metres and 11 to 13 ridges are created. The positions of the ridges are similar at different D values (5, 15, and 25 metres). A depth of 25 metres provides the most suitable amount of material by the analysis methods. Increasing the slope length causes an increase in the energy of the system, as the units fail from a greater height. Thus, the movement of the units along the flat is greater.

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[15]At 10 metres the separation between units is large and at 30 metres there is little change from 20 metre results.

The Elastic Model incorporates the first four assumptions listed in the Preliminary Model section and includes the interaction assumption of elastic collisions. Previously, it was pointed out that the occurrence of perfectly elastic interactions, especially when the front unit has stopped, is not an accurate modeling of active processes (for a dry friction model). If a collision occurs, two possible effects are an absorption of energy during the interaction (which can be revealed in a change of form of the units such as a compaction), or an override will occur. If absorption of energy results, the output would probably have a lower extension of the units, and a decreased separation from those illustrated. The number of collisions would be decreased as the units would likely close up and move together, with the energy of the rear units being passed to the front units. This effect is the basic action of a liquid flow. There still can be overriding with pulse-like transmissions transferring the energy of collisions from the rear to the front units.

Since the present study concentrates on dry friction flows, the more likely effect is that of overriding. The Hitch and Override Models incorporate hypothesized processes of override. The Override Model will be evaluated first.

The Override Model permits elastic collisions unless a unit has stopped, in which case subsequent sections will override. This model creates the greatest variety of forms because of a dependency on the two factors, time of movement and energy activated. Since elastic collisions can occur the final order of units is dependent upon TI and thus the number of elastic interactions. Two categories of features can be identified from the results of flows. The first category exhibits isolation of unit groups. These groups are clusters of two or more centres of mass, which are very distinct from other groups, when analyzed by all three techniques. The number of clusters varies from 1 to 3 at NP=10, to 1 to 5 for NP=15. When TH=35 degrees, the clusters have a greater tendency to form possibly because the units' extensions are controlled by the coefficient of friction along the base (moreso than for TH=25 degrees). Examples of these features are in Figures # 28 and 29, illustrating different inputs and analyses.

These features can be compared to Figures # 30 and 31, which show the second category, where the units are dispersed. Ridge forms are more readily identifiable in this second category, although they do not appear in a regular series or at consistent depths (heights). The Grizzly Creek rock glaciers do not demonstrate a consistent regularity of ridges either. The lobes vary in height and separation distances. The analysis which produces the least extremes of depth variation while maintaining lobe forms is the strip technique. Features produced by this analysis have a gentler transition from the talus, to the lobes, to the toe, than by the additive technique.

FIGURE 28

OVERRIDE MODEL 1

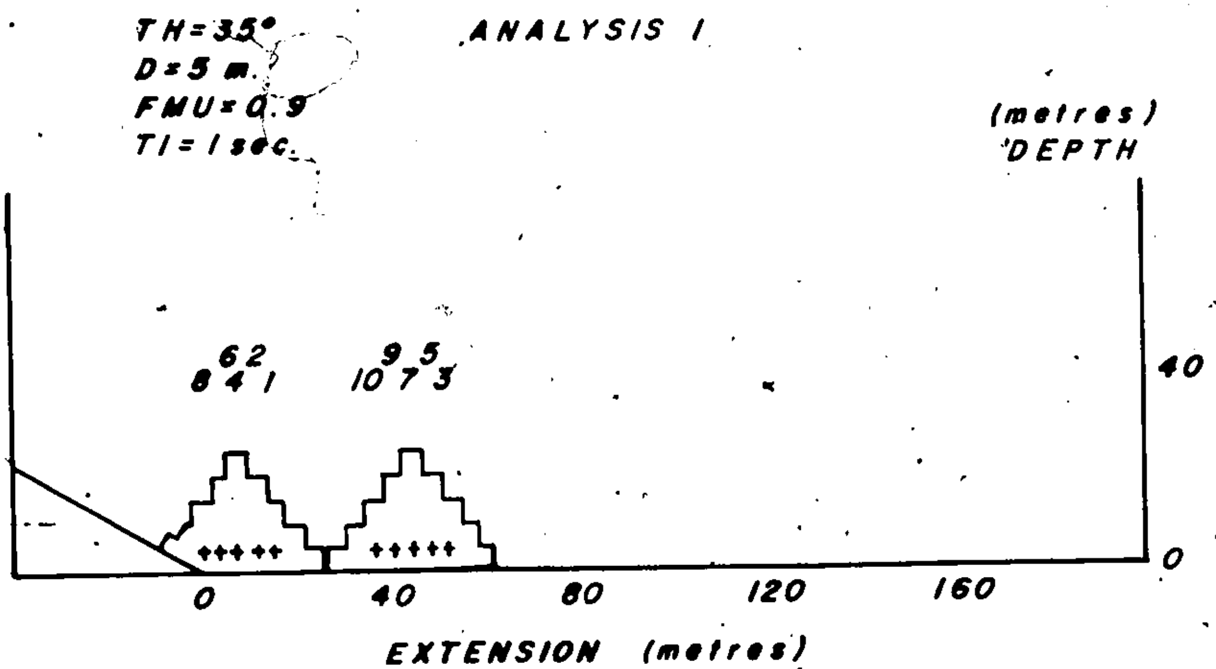


FIGURE 29

OVERRIDE MODEL II

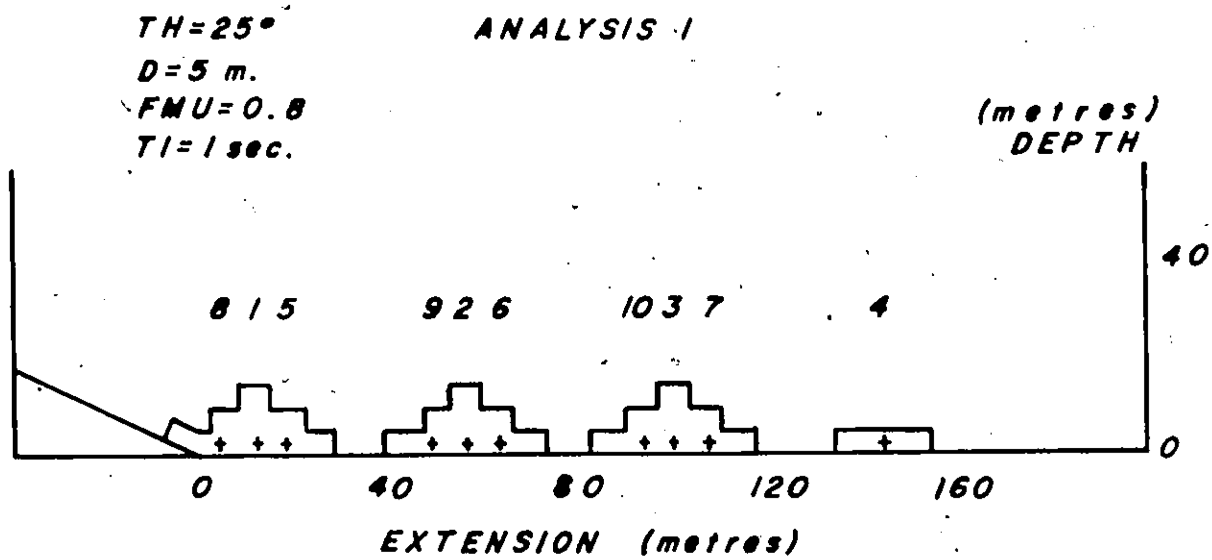


FIGURE 30

OVERRIDE MODEL III

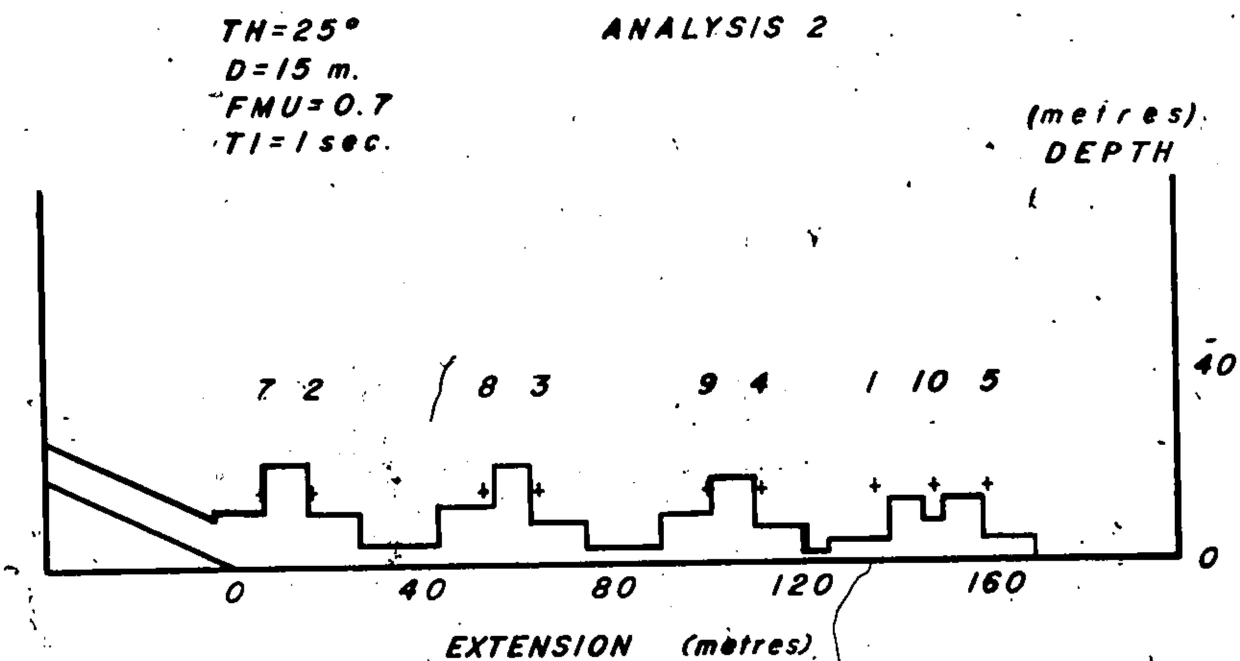
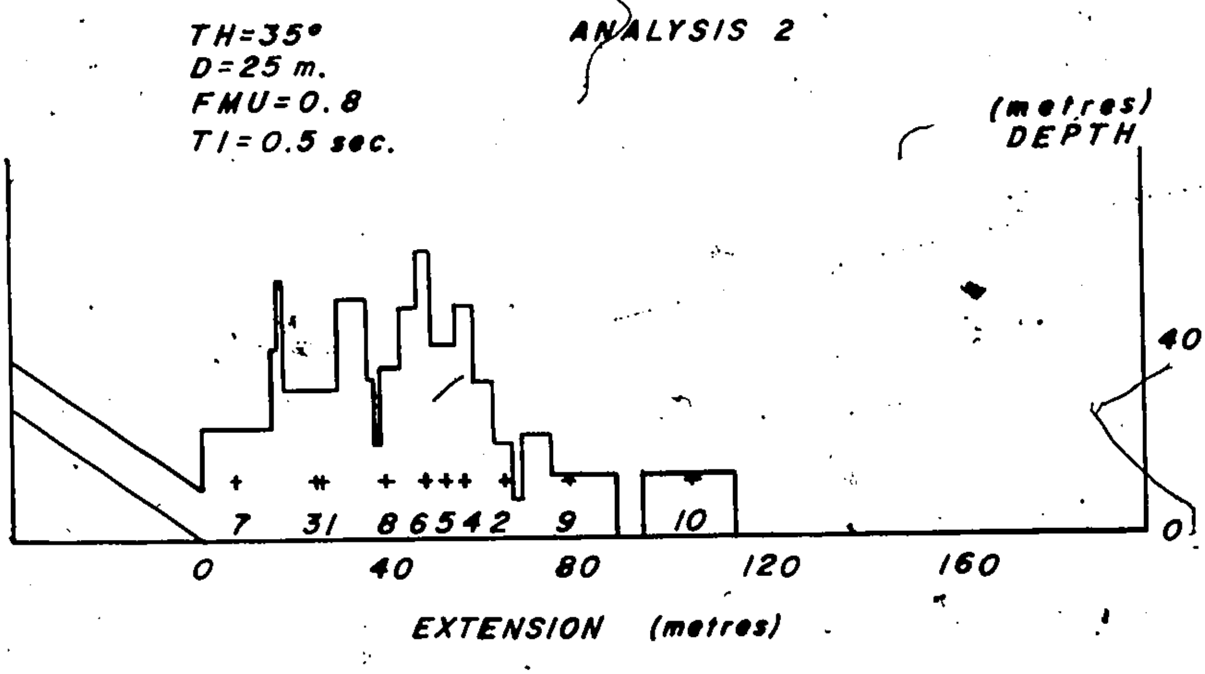


FIGURE 31

OVERRIDE MODEL IV



The extension from the slope of both form types is dependent upon FMU. The most appropriate values can be seen to be 0.7 and 0.8 as these give extensions similar to the field examples. Figure # 28 is a construction of a first category amalgamated unit. This feature is comparable to an avalanche glacier. It has an acceptably regular surface and the maximum extension is equivalent to the field example, even at FMU=0.9.

The depths of the features rely on FMU and the combination of the defined value of D, and the analysis method. FMU contributes to the dispersal of the units thus affecting the additive factor of construction. The examples used have total depth characteristics and lobe heights which compare to actual rock glaciers, since the D variable can be altered to produce this result. From the figures, the strip method of analysis can be seen to provide the most consistent results.

The Override Model produces forms which exhibit characteristics similar to the representative field rock glaciers. The 'best' model results for the ridged talus derived type of rock glacier, arise from FMU=0.7 and 0.8, varied D, NF, TI, and TH values, and analysis by the strip method. The model was extremely sensitive to changes which affected the occurrence of elastic collisions (i.e. change in TI). The greater the extension of the first units, the more suitable the constructed form. Consequently when TH=35 degrees, rock glacier type forms were not easily producible since the units stop quickly, resulting in overriding. In other cases, the main factor was the coefficient of friction. At lower values the dispersal and extension of units resulted in suitable model landforms.

The elastic collision process is important during the early development of the feature, although the override process is the crucial aspect since the order of units at the end is different in most cases. Unlike the more regular results of the Elastic Model, the Override Model produced a variety of features, some applicable and others not. The model is particularly sensitive to variation of input parameters. The operation of the model relies upon the mechanism of override. The assumption is that there is no loss of energy by an encroaching unit, an aspect which requires further discussion.

Modern small-scale talus failures produce lobes where the upslope side has an angle less than the original slope, with the downslope end having a greater angle. If a trailing section moved along the same route it would slow down on the lowered slope (decrease in acceleration) and either stop before passing the front section, or reach the downslope side and continue, with a subsequent regain in energy, which at greatest would equal the energy lost. If there is insufficient energy, then the barrier to subsequent movement is increased. The result would probably resemble an avalanche rock glacier feature.

Since each higher section in a retrogressive failure has greater energy for movement, the possibility exists that it will move past the stalled debris and continue farther. The tailings dump failures which occur move large distances downslope (up to one quarter of a mile, Personal Communication, Harrison) and lobes can be observed, therefore the Override Model considers the possibility that a trailing unit can travel over a stopped unit with no significant loss of energy (and without totally obliterating the stopped unit).

The process which is postulated to occur between moving units is an elastic collision. It has been suggested in the Elastic Model discussion that perfectly elastic collisions are not feasible in a dry friction model. If the units moved under the influence of a process where the interactions are inelastic, then one result would be the decrease of extension and separation (thus a change in shape) between units as hypothesized under the Elastic Model. Another hypothesis of interactions, is the override mechanism of the Hitch Model which will now be discussed.

The Hitch Model causes a trailing unit to absorb energy from the front unit when a collision takes place. This process occurs only if both units are in motion. If the front unit has stopped, then the simple override mechanism is active. The assumption of this model process is that as a unit overrides another moving unit, its velocity will be increased to an amount equal to the sum of individual velocities. Since the mass of the lower section effectively doubles, it will stop sooner, due to the energy transfer to the overriding unit.

At most input values, the results of model runs are simple reverse order features as outlined earlier. When FMU values are 0.7 and lower, forms similar to the Override Model are produced. The first type of forms in which the units stop in reverse order are shown in an example in Figure # 32 for the value FMU=0.7. Analyzed by the strip method, this form has irregular lobe-like surface contours. The number produced depends upon the number of failure units. A larger number of failure units also causes the feature to have a lower separation distance from the talus slope. Thus it is possible to produce a well separated rock glacier feature by decreasing the extent of the talus failure.

The second category of Hitch results is illustrated in Figure # 33. These features resemble those produced by the Override Model. The strip analysis constructs forms which can have irregular surfaces. Ridges are not readily identifiable at low values of NF. When the number of failure units is increased on a longer talus slope, the ridges are more easily recognizable.

The depth and extension of the forms of both types are again dependent upon FMU and D and can be matched to actual rock glacier features. The 'best' features produced by the Hitch Model are at PMU=0.7 with NF greater than 10, and the units in a reverse order.

Preliminary Model runs result in a reverse order of units if more than one are assumed to flow. Such a flow assumes no interactions and causes separations of values approximately equal to those of the Hitch Model results. In reality the trailing units would probably not override the front units because of the low energy differences. The hitch interaction overcomes this suspected effect because of the loss of energy of a front (lower) unit to the overriding unit. The overriding section gains energy, generally sufficient to move it more than 10 metres past the lower unit. The next section interacts and usually stops the unit at a shorter separation distance[16]. Each encroaching unit does not immediately encounter a barrier to its flow upon collision, but a sink. The lower unit is slowed down and the overriding section continues to move with increased energy. This situation describes the ideal model interaction.

In reality, the problem is the same as for the override mechanism. If the trailing units do not have enough energy to pass the barrier presented to them, then a feature similar to an avalanche rock glacier will probably result. The likelihood of

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[16]In the model runs which disperse units in other than reverse order, this effect sometimes does not occur, resulting in the more random pattern.

FIGURE 32

HITCH MODEL I

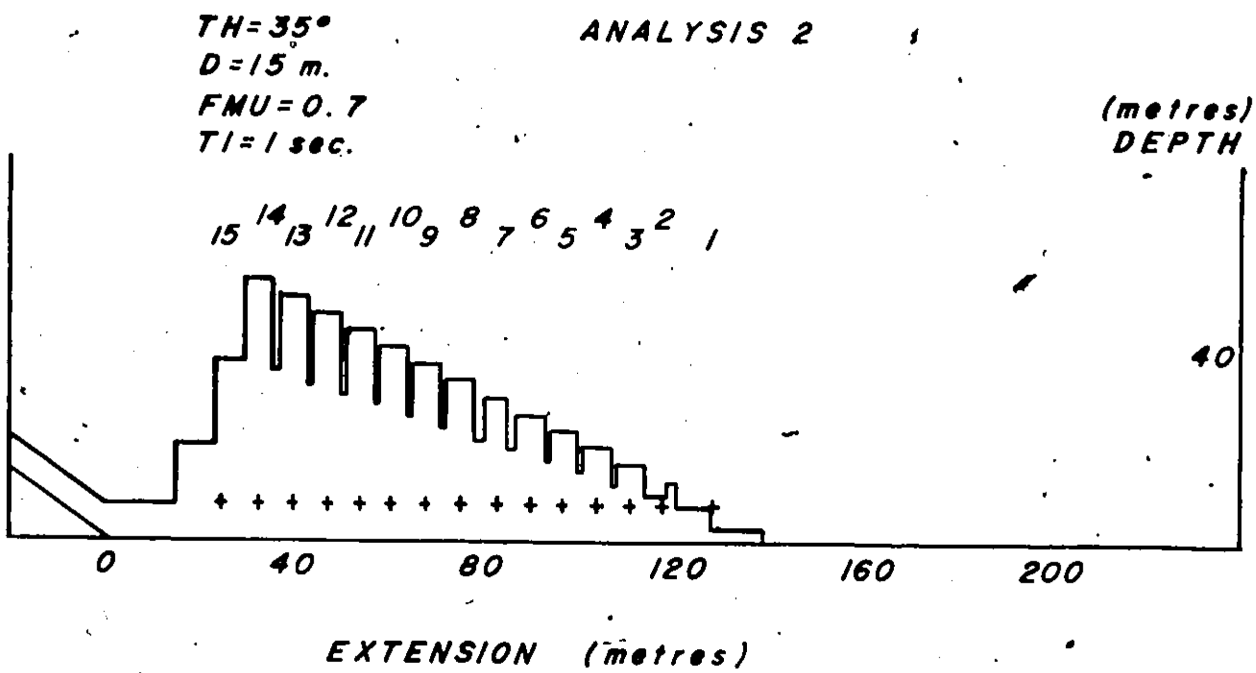
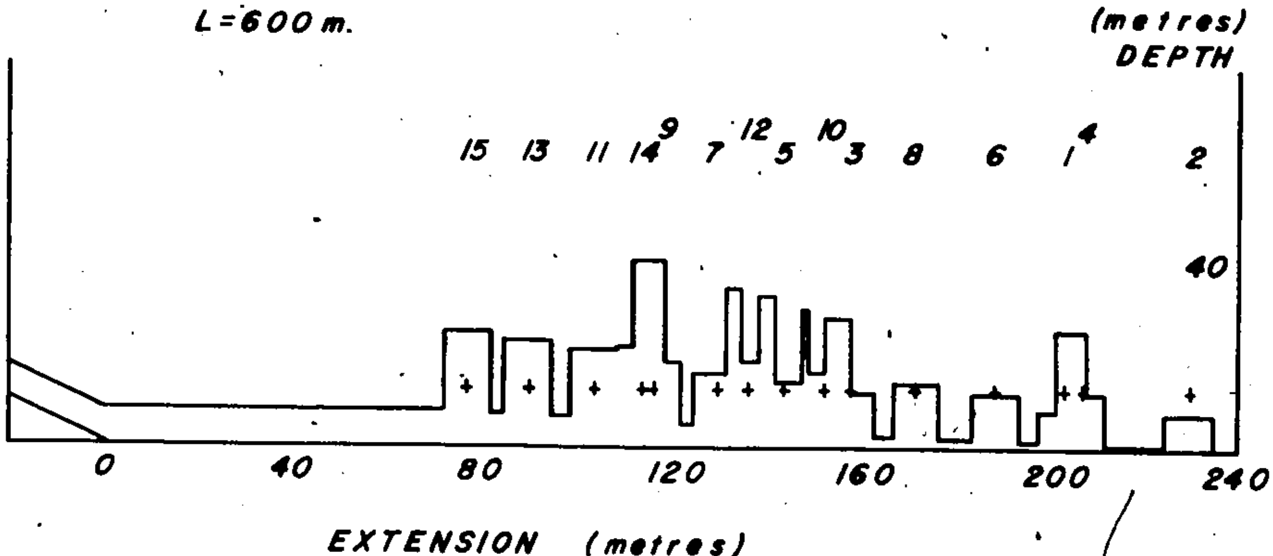


FIGURE 33

HITCH MODEL II

TH=25°
D=25 m.
FMU=0.7
TI=0.5 sec.
L=600 m.

ANALYSIS 2/3



this case happening is increased because of the mathematical simplifications utilized in the hitch process. When two units collide, the second unit is assumed to be completely on top of the first unit, although it is only in contact. The first unit stops faster because of the assumed double mass and the difference between the stop position and collision position of the first unit is added to the collision position of the second section, This difference represents the energy exchange. The second unit then continues its flow with its original movement characteristics.

If the process occurs in nature the probable action will cause only a part of the overriding unit to gain energy, thus splitting it. The section would then stop with an uneven surface contour. It is possible that this type of process could be responsible for the irregular (ridged) surface of a rock glacier. The Hitch Model is a simple attempt to consider the effects of a hitchhike mechanism.

3.6 DISCUSSION

Catastrophic processes active on a talus slope can have two inter-related roles in the evolution of a rock glacier. Supply of debris to the landform comprises one, and the second is a significant role in the development of the characteristics of rock glaciers (i.e. the surface contour). Each role can be divided into a number of potential mechanisms important to rock glacier formation. Four modes incorporating these postulates were introduced in the first chapter and are now summarized :

1. Large-scale talus failure resulting in debris supply

2. Large-scale talus failure supplying debris and producing ridges

3. Small-scale talus failure supplying debris

4. Small slips or talus failure to produce individual lobes

Figure # 34 illustrates a progression of the roles of catastrophic processes from primary importance to no applicability. The four modes are identified on the diagram. Each mode will be considered by a feasibility discussion with reference to the results of the modeling and field cases.

Mode # 1 provides a supply of debris to the lower slope and base of a talus. The avalanche of a large section of slope is evidenced in present day by the mine tailings case. A failure transports material similar to that of talus to a lower position. Such a large-scale failure could produce avalanche rock glaciers. It is feasible that the avalanche type is the first state in a sequence of rock glacier evolution. Initially the formation of an avalanche type from a catastrophic flow occurs. Subsequently, the landform may incorporate ice to a sufficient amount where the process of creep can cause movement. Through a

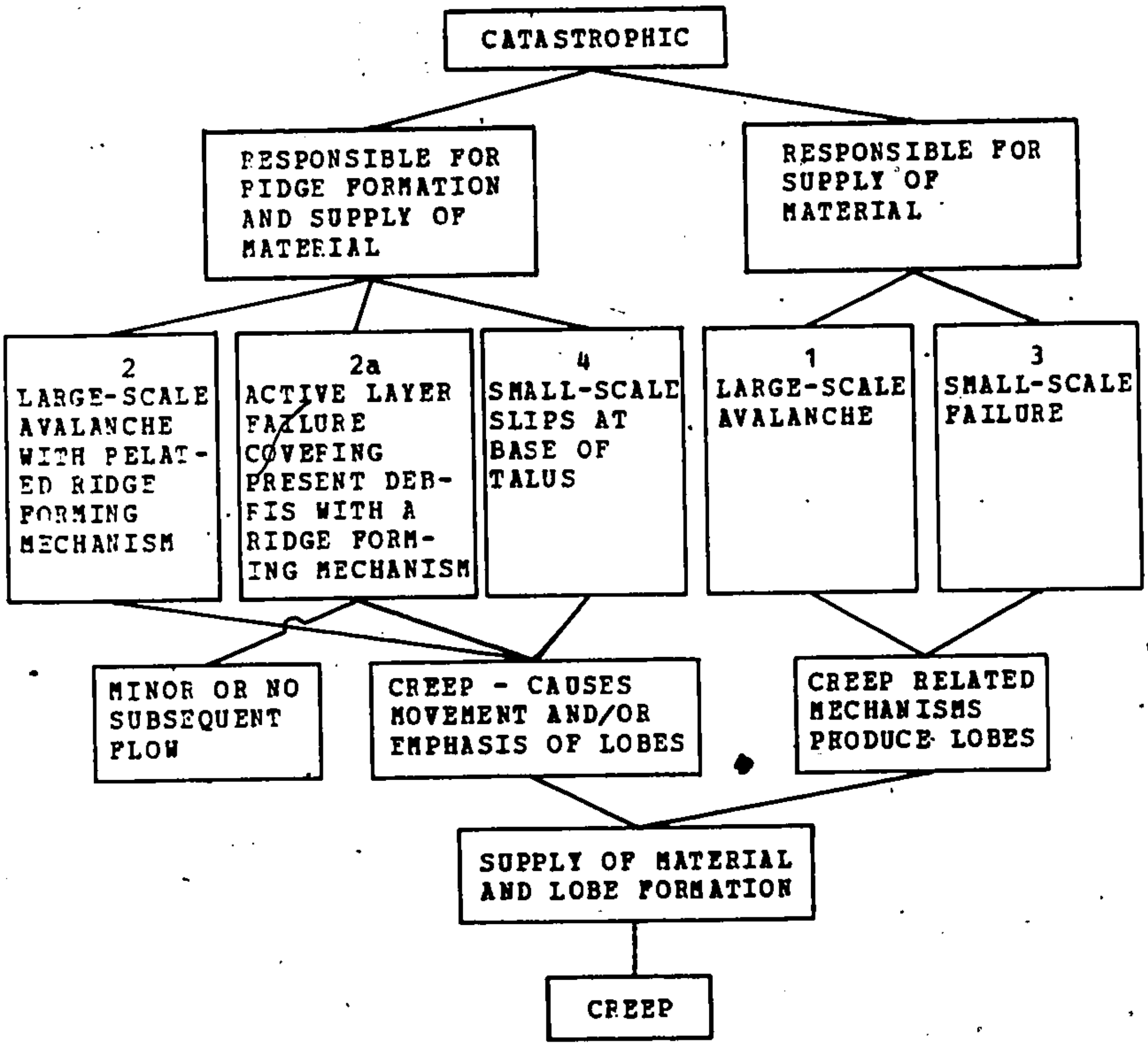


Figure 34: Framework of Rock Glacier Evolution

creep-related mechanism, the ridges may be created. The ridges could be emphasis of the surface form produced by failures of the mine tailings type. The hourglass shape of the Duke Talus Glacier supports the catastropic form although the method of ridge formation cannot be directly explained.

The modeling work produces features which are similar to avalanche rock glaciers, mainly by the override and hitch assumptions. Even if the override mechanisms do not occur, the resultant form will still be comparable (the extension would not be as great). If override is complete and the evidence of other units is hidden, although lobes may not be formed, an extended debris landform can be produced. A creep mechanism would then become active in producing the ridges. It is important to remember that actual rock glaciers do not have a slope equal to zero, but range between 10 and 20 degrees. A scale of processes can exist in a talus complex in which catastrophic processes are more significant at higher angles (talus angles), and creep processes are active at lower angles (rock glacier angles).

A retrogressive failure is not necessary within Mode # 1. The Preliminary Model with NF=1, can produce the required form, although the extension in a real flow would be reduced from that caused by the model, as previously discussed.

The mechanism which creates surface lobes is not adequately explained by any research at present. That it is creep related is the proposal of Mode # 1. The postulate of Mode # 2 is that the evolution of ridges is caused by a large-scale catastrophic flow. The field evidence for this proposal is the retrogresive failures observed in the mine tailings dumps. The final surface form of these incidents is a series of ridges down the slope.

There are two possibilities for the formation of ridges during an avalanche. The first is that a mechanism inherent to the phenomenon causes the alternating crests and troughs. This mechanism may be related to :

1. a retrogressive action

2. a wave-like impulse from either the initiation of movement or change of slope

3. or finally, a process which is not understood at present

Some of the modeling work was an attempt to consider the retrogressive factor, and postulated processes of the third category. The Override and Hitch Models assumed two different methods of creating a lobed feature. The forms which resulted had lobe-like surfaces on features resembling rock glaciers. The drawbacks of the specific models were considered, but it was possible to produce rock glacier forms within a dry friction flow.

The occurrence of these mechanisms is not easily justified in natural locations unfortunately.

The second possibility of lobe formation in a large-scale movement is a cohesive flow. The cohesion can be supplied either by interstitial ice or by water in a viscous flow. The ice factor is of doubtful consequence except that it can supply moisture to the debris. The presence of high porewater pressures is one initiator of failures. Upon failure of a talus any interstitial ice will be converted to water because of the friction. The presence of water during the active period of rock glacier formation is probable. If the amounts were significant, a mud-like flow could have occurred. Present day field examples describe these wet movements in periglacial areas (Spitsbergen, Canadian Rockies). If the flow was retrogressive or by some process an impulse wave is produced, the formation of lobes is a natural conclusion. The Duke Talus Glacier could be the classical example of such a flow. The hourglass shape and the outward spread of ridges onto the base are characteristics of a viscous process. The irregular surfaces of all of the rock glaciers could be the result of surges (failures) of liquidized debris.

The Elastic Model assumed an ideal case of the liquid type type of flow. Perfectly elastic collisions would not actually occur, thus the separation of the units illustrated in Elastic flows would be reduced. In this case, the features produced would resemble talus derived rock glaciers (higher units could also move onto the base of the talus).

Some of the models also examine the possibility of a failure of limited depth (restricted to the active layer) which moves on to a base of debris. The active layer material is wet during warmer periods, thus a liquid flow is feasible. With an inherent ridge-forming mechanism, rock glaciers could result, especially if the flow overrides an avalanche form. This mode is suggested as one possibility although it cannot be tested accurately.

If creep does occur in either of the two possibilities suggested above, then it will explain any motion observed on rock glaciers in present times. Within Mode # 2, steady-state flow is of little significance during development of form, but in Mode # 3, creep is of major importance in contributing towards movement, with debris being supplied by small-scale failures. Avalanches contribute material to the head of the rock glacier. Creep may be initiated by a critical amount of material or it could be an ongoing process. This mode has been suggested to be responsible for lobe formation (Barsch, 1977), but to explain a lobe separating from further debris slides is a problem.

The author considers that the most probable creep explanation for rock glaciers includes a catastrophic mechanism. Mode # 4 suggests that small slips at the base of a talus slope produce individual ridges, then move by creep down the lower slope of the rock glacier bed. Evidence for this mechanism exists on the slopes of Grizzly Creek and the Duke River. The slopes at the head of each rock glacier have a series of slips which appear to continue onto the rock glacier. Figures # 7 and 8 show these type of slips on the Duke Talus Glacier. They are not as well defined in Grizzly Creek, but they are visible. As the rock glacier creeps downslope, a slip follows and is incorporated as a lobe. As the material creeps away at the junction between talus and rock glacier, another slip occurs and so on.

This last mode is an attractive sequence to employ to describe the evolution of a rock glacier, since some field evidence can back it up, and the accepted importance of creep is included. Some problems of interpretation arise, unfortunately. What caused the initial formation of a lobe and its movement away from the slope? It is possible that all of the talus is slowly creeping down the slope. Perhaps as the material moves onto a lower angle slope, there is a mechanism which causes the talus to separate into ridges of material. The possibilities of creep mechanisms are numerous, however the field evidence disputing universal acceptance of the steady-state flow was outlined.

The modeling work did not directly consider the last two suggested modes since the role of catastrophic processes is to supply material by small-scale failures. These minor movements can be taken as limited failures within the Preliminary Model. There is little value in considering such a simple model because the interrelation with creep processes is complex and difficult to determine. The two general types of processes, creep and catastrophic, need to be examined together, and that is beyond the scope of this study.

3.7 ASSUMPTIONS

The limitations of any modeling work derive from the simplifications of reality necessary to permit operation of the model. Application of the results to natural situations is dependent upon the required assumptions providing an acceptable relationship between model and reality. The action of each postulated flow mechanism has been discussed within each model. The general assumptions and their effects will now be considered.

3.7.1 Single Angle Slope

Alpine talus usually exists in one of two general profiles. The first is at an inclination which can be averaged as a single angle with a discontinuity between slope angle and base. The second profile has an upper single angle with a basal concavity (Statham, 1976). The model slopes are of the first type, although the second type is more common. In modern slope processes one of the influences on travel distance of failure sections is the change in slope. Failed units in isolated movement will reach the base of the slope whereas if the angle was lowered, they would not necessarily have sufficient energy. This situation explains one anomaly between the model and reality.

As an example, units in motion on a slope will cease to accelerate positively at critical angles, dependent upon the angle of internal friction and the value of FMU, (thus coefficient of friction) as listed :

FMU=0.7	TH=25 degrees	Critical angle=18 degrees
FMU=0.9	TH=25 degrees	Critical angle=23 degrees
FMU=0.7	TH=35 degrees	Critical angle=26 degrees
FMU=0.9	TH=35 degrees	Critical angle=32 degrees

At the appropriate critical angle, the slowing effect of friction exceeds the acceleration due to gravity.

The models actually assume the extreme case where units will slow down at the critical angle and undergo the movement conditions of an angle of 0 degrees. The critical angle occurs at XTR in the model flows. Examining the Grizzly Creek glacier profiles will aid in clarifying this point.

If the original Grizzly talus exhibited a basal concavity then the highest this concavity would have reached on the slope is at the present junction of the talus and rock glacier. Above this point, the slope existed at a single angle (average angle). In comparing the model slopes to a concave type of slope in Grizzly, the value of XTR is set at the talus/rock glacier junction (which does not actually exist in the pre-flow situation), and not at the talus/valley floor junction. Thus the values of extension of the actual rock glaciers would increase approximately 50 metres over the values of a single angle type. The value of slope length simply refers to the length of talus above the basal concavity.

In measuring the flow the calculations of a single angle (zero angle base) will underestimate the extension values of a movement to a concave base. Furthermore, the depths of a feature which has moved onto a base of talus will provide an overestimate of the volume of material which has flowed. Consequently a talus avalanche may be responsible for only the surface contour with possibly an extension onto the valley floor. In the described situation a shallow slab failure (five metres and less) could be responsible for the initial formation of a rock glacier (subsequent flow, if there is any, would be by creep).

In justifying the override of stopped units, a difficulty was encountered due to the possibility of a reverse slope being formed after a unit stops. A trailing unit might stop before override was completed. On a concave lower slope, the effect of reverse slopes is decreased because fewer will form. Since the slope has an inclination, stopping units will spread farther and the angle that they present to oncoming units will be less than that on a flat (the actual slope angle will subtract from the stopped unit's upslope angle).

The situations described above show that the zero angle base is the limiting example of a field slope. If the talus exists at a single angle then model slopes are similar. In the case where a concave base exists, the results of model flows are comparable to those that might occur. The concave base actually provides better justification for override mechanisms to be significant.

3.7.2 Retrogressive Failure

The assumption of a retrogressive failure was made because of the observations of the mechanism in mine tailings dumps. Since the resultant features exhibit ridges, the mechanism was assumed to have significance in the formation of lobes on talus derived rock glaciers. The retrogressive failure is the basis of the modeling attempt to develop lobes. In the modes where the catastrophic processes are significant only for the supply of material, the model units provide a simplification to examine the movement of a slope failure.

To examine the debris supply role, NP can be set at low values and the movement examined. Unfortunately, the model considers the motion of the centre of mass so that the extension of the front of the unit on to the base is not influential until the centre of mass reaches XTR. Consequently, the model runs with NP=1 and W of the order of L, result in values of extension which are probably too high.

As suggested, the basis of the modeling work is that the retrogressive mechanism is significant in the evolution of the surface form of rock glaciers. The contribution of the models to other suggested modes is discussed in the next section.

3.7.3 Analysis Methods

The analysis methods were discussed when first introduced and will now be considered in light of their results upon final forms. The first technique of maintaining unit size and shape provides rock glacier type results for only the Elastic Model. For the other models the features have too great a depth or too large or irregular a variation. In a real situation, the maintenance of shape is dependent upon cohesion of a unit. The possibility of cohesion of the units in a flow will be discussed in the next section.

The strip method permits a loss of material by a moving unit and results in less extreme variations in the feature surfaces for the Hitch and Override Models. In a real flow, this type of movement is probable. With motion along the slope, debris will be deposited. The problem is to estimate the amount of material that will be stripped off. The technique defines an amount of either 0.5 or 1 metre for every distance W, travelled. The effect is to produce landforms which have dimensions similar to rock glaciers. That the mechanism is possible in nature is a proposal of this study.

Utilizing the third method does not directly account for the total volume of the material which failed, but it does allow for an increased dispersal of the units. The method was used as a modification of the first two techniques when neither resulted in suitable features. Generally the effect was to decrease the depth and the variation of the surface contour. The unaccounted material could moderate the vertical changes in surface heights which are inherent to the analyses. In the natural context, the use of the last two techniques implies a greater dispersal of the mass of a unit. Since talus failures result in gently sloped triangular shaped lobes, this analysis compares with actual observations (Jahn, 1967).

The illustrations of model results and analysis show discontinuous height variation. If the units are assumed to stop in a triangular shape, the dimensions of the triangle are not easy to define. Another method is to picture the failing unit as a trapezoid. Upon cessation of movement, the overhanging part of the unit (at the front) would collapse to leave a sloped front. In reality the back slope would be more gently angled, but the resultant form would be similar to the half width analysis, since the trapezoid does not have a full depth for the value of W. The trapezoidal shape is more conducive to failure, since the front of a unit can initiate motion by sliding along the interface with the next unit. This method is one possibility to smooth out the model landforms. In actual failures, the unit would be more dispersed with lower peaks around the centre of mass.

3.7.4 Coefficient of Friction

With the recent contoversy in geomorphology over the meaning, measurement and comparison of the angles of internal friction, repose , and slope stability, the selection of a definition for the coefficient of friction is difficult. Gerber and Scheidegger (1974) use the classical definition, more recently favoured by Carson (1977) that a slope stands at the angle of repose, which is approximately equal to the angle of internal friction. Statham (1976, 1977) argues that the angle of internal friction of a material is generally 5 degrees greater than the angle at which a talus forms. He argues that the classical studies, definitions, and laboratory measurements of the angles of repose and internal friction are limited in application to actual talus. The controversy will continue, but for the initial simple models of talus failure, the angle of a talus was assumed to be equal to the angle of internal friction.

The coefficient of an angle is mathematically defined as the tangent. Gerber and Scheidegger (1974) describe different values for coefficients of friction, dependent upon the mechanism of movement of a section of talus (also single rockfall events). They state that modern debris slides do not reach the bottom of a slope and that the coefficient of sliding friction is greater than the tangent of the angle of internal friction[17]. For the mechanism of rolling, Gerber and Scheidegger apply a value approximating tan ϕ_i since rocks can reach the bottom of a slope. They do not consider that a changing angle of movement on a concave base will stop a section which has initial energy.

The modeling of a rock glacier which extended out from the base of a talus through catastrophic processes, requires that the coefficient of friction is less than the tangent of the angle of internal friction. A failed section will then reach the bottom of the slope. Consequently the coefficient of sliding friction can be lower than the tangent, or a different process or lubrication is active. The value of the coefficient of fric-

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[17]As mentioned previously they also require an initial energy for movement of a slope section. otherwise at values greater than tan ϕ_i, the section would not move. Failure does not produce energy, it simply changes potential energy to kinetic energy. As soon as shear stress exceeds shear strength there is flow with no energy input.

tion which is active was varied from 0.5 to 0.9 to consider the stated role.

There is the possibility that large scale failures move under a different lubrication or mechanism than smaller modern failures. This factor can explain the different values of coefficient of friction for the present study.

3.7.5 Two-dimensional Model

In the modeling of the catastrophic movement, a two-dimensional slope was used. The flow characteristics of the talus are examined for an imaginary line assumed to be along the centre line of the slope and subsequent rock glacier. No friction is assumed along the side faces of a unit (imagining that the unit is three dimensional with a z component of width dz). It is a standard technique to assume that in this case the z measurement of a unit is great enough that side effects can be ignored. The rest of the model slope will move similarly to the defined section.

On natural talus the side effects cannot be ignored since they are the most likely cause of the transverse arcuate shape of the ridges. The friction at the sides is significant enough to slow the movement of the outer edges of a unit flow, resulting in the arcuate form. The two-dimensional assumption is not restrictive on model relation to natural landforms[18].

3.7.6 Transition Assumption

The transition of a unit from movement on talus to movement on the base occurs when the centre of mass intersects with the line y=D/2. The unit is assumed to maintain its shape therefore the centre of mass cannot go lower. Because of the operation of the models, the transition does not restrict the collision process, although the transition does cause the unit to move under different forces. The restriction on the transition is the width of a section. If the value of W is large, then the front portion of a section will slow down to probably result in overriding by the rest of the unit. Since the values of W were less than 30 metres, the problem was assumed to be insignificant.

1* Occasionally the lateral extension of the moving talus is restricted by valley form or deposits. This is one possible explanation for the formation of longitudinal ridges.

Chapter IV

CONCLUSIONS

Determining the interrelation between talus and talus derived rock glaciers is one of the main goals of this study. The work centred upon potential contributions of catastrophic processes. From the basic assumption that a talus could fail retrogressively, models were developed to attempt to produce rock glacier features. A number of mechanisms were postulated to be responsible for the ridge formations identified on field rock glaciers, and in the movements of mine tailings. To permit operation of the models, simplifications of complex factors were necessary. These assumptions were examined throughout the thesis to evaluate the feasibility of the models.

The critical factor of the work was the assumption that a significant portion of a talus could avalanche. Conditions that existed at the time of slope development were speculated in the introductory chapter. The climate combined with the effects of glacial ablation (probably due to a warmer, wetter climate) could have resulted in slope conditions which caused oversteepening or instability in talus. Increased quantities of moisture, increased supply of debris, or removal of basal support (either through ablation of ice or basal removal due to glacial outwash), could induce failure. Creep could be active but as a prelude to, and a cause of catastrophic flows.

A variety of talus and talus derived features, with an apparent range of ages, exist in the Grizzly Creek area. This random development of rock glacier forms was suggested to be supportive of catastrophic processes rather than steady state ones. The dual movement nature of the Yukon rock glaciers (Smith, 1973 also observes this phenomenon) is felt to be indicative of catastrophic movements, since a later creep movement should have been mirrored by a reactivation in the original feature. The stability indicated by the vegetation on the lower rock glacier areas does not support this occurrence.

With the evidence that catastrophic flows can produce ridges (mine tailings failures and Mathew and McTaggart, 1969), the process was considered to have a significant role beyond simple debris supply. The Preliminary Model examined the movement of isolated sections by a dry friction flow, to supply material, while the interaction models postulated mechanisms by which a retrogressive failure could move to cause rock glacier characteristics. The difficulty of explaining ridges by a large-scale flow, exists in postulating a mechanism of lobe formation. There is no basis to the work beyond the field evidence. Three categories of mechanisms were suggested :

1. retrogressive action involving flow mechanisms

2. wave-like impulse due to initiation of movement or change of slope

3. unknown influences

Each category can be split into non-cohesive and cohesive (or apparent cohesion) dependencies.

If a talus avalanches as a single mass, a mechanism which would result in lobe formation is difficult to justify. In either a cohesive or non-cohesive flow an impulse wave could result in alternating crests and troughs but an initiating cause is unknown. A Preliminary Model run, with a full slope failure (MP-1) was a simple attempt to produce an avalanche type of rock glacier. The drawbacks of the model were suggested with modifications being left to future work as the complexity of the flow is beyond the scope of this study.

For a retrogressive failure, two situations can occur; either the later units will override or their energy will be transferred to the earlier-failing sections. Examining the first case, the lower units may be completely disguised (covered) or the surface contour may indicate their presence. The Hitch Model (and the complete flow of a Preliminary Model slope) assumes that the location of the centre of mass can be identified as a concentration of debris or a lobe, whether it has been overridden or not. The model predicts a similar effect independent of cohesion and produces rock glacier features. The feasibility of the mechanism is based on the possibility of overriding without obliteration.

The second situation assumes an energy transfer to a lower section. The Override Model incorporated aspects of both situations. Energy transfer to a lower unit occurred after a unit had stopped. The results were a variety of features, some showing ridged surfaces and others appearing as avalanche types. The model is dependent upon both the transfer of energy and an override without obliteration. The override is possible, independent of cohesion, but the energy transfer is more probable for sections which have cohesion or an apparent cohesion.

The presence of significant amounts of water was suggested due to the conditions during the period of rock glacier formation. Water could have supplied a cohesive property to result in the elastic type of collision. The Elastic Model assumed solely elastic interactions. The production of talus derived features was simple by the model. If there is no cohesive factor then the model loses its basis. One argument against a cohesive flow is the low percentage of fines in fresh talus. This proportion can increase as a section moves downslope due to the high pressures. In addition, the water content will increase if interstitial ice is present (friction causes the ice to melt). A mud-like flow is a feasible explanation for rock glacier features.

The passage of impulses in a cohesive failure is also valid, as is the possibility of impulses due to changing conditions (i.e. slope transition) in non-cohesive flows. These mechanisms were not modeled in the present work due to the difficulty of postulating their significance. The third category of unknown influences can include factors of the first two categories. As this study suggests, all catastrophic aspects of rock glaciers are actually unknown.

The models were applied to a general framework of rock glacier evolution illustrated in Figure # 34. Two roles of catastrophic processes were identified, the supply of debris and the development of rock glacier characteristics. All of the models are applicable to the supply role. Without considering the feasibility of the models, the success in producing characteristics of talus derived rock glaciers varied. The viscous form of the Elastic Model produces the most suitable rock glacier features at values of FMU=0.8 and lower and D=25 metres (at most other values of input parameters). The extension and creation of the lobes is comparable to Grizzly Creek examples. The override mechanisms (hitch and override) resulted in suitable forms for FMU=0.8 and lower (best results at FMU=0.7), but determining their significance during movement is difficult, if not impossible. Other mechanisms which have not been postulated could be active in a catastrophic flow (especially if the retrogressive failure assumption is deleted).

The interaction models fit under Modes # 1 and 2 in the evolutionary framework. A single large scale failure can fit either mode since debris supply is accounted for, and there is a possibility that one of the hypothesized flow mechanisms may be active in causing a ridged surface contour. The possibility was discussed although the justification is abstract.

Assuming single failures of limited extent suits Mode # 3. The Preliminary Model can be utilized to fit this role of debris supply, but modifications are necessary to consider movement on different slope profiles. The mechanism of flow must also be examined to determine suitable values of input parameters.

Small slips on the lower talus slopes are not abstract as they exist in field situations. Evaluating Mode # 4 should be the aim of other studies on rock glaciers, since it incorporates the accepted creep mechanism. Unfortunately suitable process approaches are not found, as outlined in the first chapter.

The major conclusion of this study is that talus derived rock glacier development is dependent upon the relation of processes active on :

1. the talus slope

2. the rock glacier

Modes # 1,2 and 4 are the most probable sequences of evolution for rock glaciers. They provide for a continuity between catastrophic processes on the talus (small-scale slips or large-scale failure) and creep processes on the rock glacier. A scale of development of talus derived features is proposed which combines catastrophic and steady-state movement :

1. large-scale failure on talus to produce avalanche forms
2. catastrophic processes active at higher angles to produce characteristics of talus derived types
3. creep processes active on lower angles to modify # 1 or 2 features

This scale includes possible connections between talus and rock glacier forms. The processes are dependent upon slope angles, although other conditions can alter or prevent activity.

While considering the previously dismissed catastrophic factor, the study raised a number of sidelines which require future examination. The use of a coefficient of friction based upon the characteristic angles of a slope is justified, but it must be applied correctly. Gerber and Scheidegger (1974) state that for sliding debris the frictional coefficient is greater than the tangent of the angle of internal friction. They assume that the sliding mass has initial energy and that the debris does not reach the bottom of the slope. The stoppage of the slide could be due to the decreasing slope, and failure generally occurs under equilibrium conditions such that there is no initial energy. Statham (1976) utilizes the tangent of a dynamic angle of friction in his work on rolling discrete particles. The use of this term does not allow for the greater dependency upon impact frictional forces rather than frictional force in the movement of rolling particles. It is proposed that the best method of defining the coefficient of friction for moving debris, is to take a factor of the tangent of internal friction (instead of defining other angles to fit sliding or rolling situations).

This definition causes model flows to move farther for lower angle slopes due to the increased influence of the coefficient of friction over the slope angle effect. The effect would be expected to result in field observations of greater extension of talus derived rock glaciers in materials with lower angles of internal friction (which are defined to stand at lower angles). The result could be masked by different processes of sliding (i.e. the value of FMU may be slope dependent).

Another conclusion of the modeling is that the extension of rock glaciers is related to the slope length of talus (also suggested from field observations by Smith, 1973). Creep studies have not usually related the supply of debris to the movement of material. If there is a continuous creep process fitting under

Mode # 4, then a continuous movement of material from talus to rock glacier may be possible. This proposal requires that creep be of greater significance at lower angles. Future studies must evaluate this hypothesis.

SUMMARY

The emphasis of the modeling has been on catastrophic processes, but the emphasis of the study has been on the relationships between talus and rock glacier and catastrophic and steady-state processes. The conclusion of the study is that talus and talus derived rock glaciers are not distinct features, but are present as a talus complex. Similarly, catastrophic and steady-state processes are fused within a framework of continuity of action. The catastrophic factor must be re-evaluated in field and theoretical studies. Until the complete framework is constructed, rock glaciers will continue to be obscured by a fog of misinterpretations.

Appendix A

DEVELOPMENT OF PRELIMINARY MODEL

The mathematical development of the model is a progressive application of basic algebra. The slope is defined using equations of lines. The sectioning of the slope into units is also mathematically defined by equations, and the centre of mass of each unit is described by the intersection of two lines.

Understanding of the following mathematical steps will be facilitated by referring to Figure # 12. (Computer symbols will be used for arithmetic signs, specifically for multiplication, * , division, /, squaring, **, and square root, SQRT)

The slope is defined by line I in Figure # 12 ; the equation being:

y=-H/HL*x+H (I)

H/HL=tan(TH)

y=-tan(TH)*x+H

Line #II defines the depth of the units, thus the depth of failure. Calculating the equation:

Since y=-tan(TH)*x+(H-d) in Figure # 12

D/d=cos(TH)

therefore d=D/cos(TH)

Therefore

y=-tan(TH)*x+(H-D/cos(TH)) (II)

Line III describes the parallel (to the slope) centre line of the units.

y=-tan(TH)*x+(H-D/2) from Figure # 12

d/cos(TH)

d=cos(TH)*D

Therefore

y=-tan(TH)*x+(H-D/(2*cos(TH))) (III)

Line IV defines the parallel centre line of failed units that have been transferred to the surface of the slope.

From Line III

y=-tan(TH)*x+H+D/(2*cos(TH)) (IV)

To calculate the coordinates of the centres of mass of the units, perpendicular line equations are required.

Line V defines the upper edge of the first unit. Since the slope(mathematical) of two perpendicular lines have the following relationship :

Slope of line 1=m1

Slope of line 2=m2

m1 * m2 =-1

Thus the slope of perpendicular lines to the natural talus slope will be:

m=1/tan(TH)

Therefore from y-intercept, b=H-D/cos(TH)

and m=1/tan(TH)

y=x/tan(TH)+(H-D/cos(TH)) (V)

Line VI is the perpendicular centre line of the first unit.

Same slope as for V

The value of the y-intercept is:

b=H-d-d1 from

w/(2*d1)=sin(TH)

d1=w/(2*sin(TH))

b=H-D/cos(TH)-w/(2*sin(TH))

y=x/tan(TH)+(H-D/cos(TH)-w/(2*sin(TH))) (VI)

A general centre line equation for the Ith unit is:

y=x/tan(TH)+(H-D/cos(TH)-(I-0.5)*w/sin(TH))

To evaluate coordinates, the intersections of each pair of centre lines are taken.

Let SL1=-tan(TH)

SL2=1/tan(TH)

Therefore SL1=-1/SL2

The point where III intersects with the general form of equation VI is the centre of mass of the Ith unit.

SL2*x+(H-D/cos(TH)-(I-0.5)*w/sin(TH)) (VI)

=SL1*x+(H-D1(2*cos(TH))) (III)

Therefore

x=-(D/(2*cos(TH))+(I-0.5)*w/sin(TH))/(SL1+1/SL1)

To calculate the y component, x can be substituted into either of the equations.

When failure is assumed to occur, a unit is transferred to the surface. This transfer is done by keeping the y-component the same, thereby not affecting the potential energy of the section. To calculate the new coördinate, substitution of the y value into IV gives:

$$x=(y-H-D/(2*\cos(TH)))/SL1 \quad \text{(VII)}$$

The failed unit will now move down the slope and the mechanics of the movement can be determined by a straightforward application of Newtonian Mechanics. There are several ways to proceed. One method suggested in Chapter 2 was to calculate the travel distances on the slope and along the base. These values can be obtained from the simple energy considerations which were outlined.

A more comprehensive approach will include the calculations of time and velocity, and provide a better basis to the modeling. Thus the initial model will use another approach to examine the travel of the units.

Given initial conditions and the active forces, the dynamics of a unit can be simply determined as follows:

At time, t=0

Initial velocity is zero

Initial position is zero

Forces active

i. Gravity FG=M*G*sin(TH)

ii. Friction FF=M*G*cos(TH)*MU

FU=FG-FF

Force=Mass*Acceleration of Unit (A)

M*A=M*G*sin(TH))-M*G*cos(TH)*MU

A=G*(sin(TH)-MU*cos(TH)) (VIII)

Let K1=sin(TH)-MU*cos(TH)

Therefore A=G*K1 (VIIIa)

To calculate velocity at time T, integrate between 0 and T, with respect to t.

A dt= G*K1 dt

V=G*K1*T+C1 (IX) where v=velocity

C1=initial velocity

Therefore V=G*K1*T when C1=0

To calculate distance traveled at time T, integrate again between 0 and T, with respect to t.

V dt= (G*K1*T+C1) dt

TD=0.5*G*K1*T**2+C1*T+C2

where D=distance

C2=initial position

Therefore TD=0.5*G*K1*T**2 (X)

when C1, C2 = 0

The above analysis describes a moving unit on the slope. The forces change when the unit transfers to the base at the transition point. This transition point is the x,y coordinate where the line y=D/2 and IV intersect.

Equating $D/2=SL1*x+H+D/(2*cos(TH))$

Therefore $x=(D/2*(1-1/cos(TH))-H)/SL1$ (XI)

$=XTR$

XTR will designate x at transition

VTR will designate v at transition

TTR will designate t at transition

When the centre of mass of a unit reaches this point, the unit is instantaneously transferred to movement along the base, with the changed unit force:

$FU=-M*G*MU$ from $FF=MU*N$

Therefore $A=-G*MU$ (XII)

rIntegrating

$V=-G*MU*(t-TTR)+C3$ where $C3=VTR$ (XIII)

Integrating again

TD (along base) $=-0.5*G*MU*(t-TTR)**2+C3*(t-TTR)+C4$ (XIV)

where $C4=XTR$

For the simple initial computer model, the output only requires the calculation of the final stop position, STPOSN, of each unit, the extension from the base, EXT, and the time of travel, TS. From the above relationships the necessary equations to calculate the parameters for the Ith unit are :

$STPOSN(I)=XTR+VTR(I)*(TS(I)-TTR(I))-MU*G/2$

```
        *(TS(I)-TTR(I))**2                          (XV)
TS(I)=VTR(I)/(MU*G)+TTR(I)                          (XVI)
VTR(I)=G*K1*TTR(I)                                  (XVII)
TTR(I)=SQRT((YAF(I)-D/2)/sin(TH)*2/(G*K1)           (XVIII)
EXT(I)=STPOSN(I)-XTR                                (XIX)
```

The construction of the computer model is straightforward now that the theory and equations are outlined. Referring to the attached program, the first section defines the parameters and calculates the other input values. The coordinates of the centres of mass are calculated before and upon failure. Then the final position, velocities and times of movement are determined. Since the y values result from substitution into one of two intersecting equations, an accuracy check is made by substitution into the second equation. That is the function of ERR1(I). The output of the program gives the basic parameters as listed, the error function, and the extension of the unit from the base along with its time of travel.

Appendix B

DEVELOPMENT OF INTERACTION MODEL

The Preliminary Model development in Appendix A outlines the basic definitions and movement characteristics of a slope failure. This Appendix will examine the theory of collisions between units. The final computer models of the different collisive hypotheses are included at the end to summarize the model construction. The more general case is covered in the section in Methodology, Chapter 3.

The slope has been defined and the position of the units that fail can be calculated prior to movement as for the preliminary model. In the interaction model, the time aspect of failure is of prime importance.

The first unit to move will do so at time, t=0. Each subsequent unit will move at a time defined by a factor of the time interval between failures, DT. The second unit will move at DT, the third unit at 2DT, and so on. As an example, consider a failure of NF units labeled from 1 to NF, where the unit NF moves first. The time of failure of the ith unit, T(I) is

$$T(I) = (NF - I) \cdot DT$$

To calculate the non-interaction parameters of movement the following equations are easily developed, by substituting (TTR(I)-(NF-I)*TI) for the time in the appropriate equations from Appendix #1.

from equation (XVIII), Appendix A

```
TTR(I)=SQRT((YAF(I)-D/2)/SIN(TH)*2/(G*K1))+(NF-I)*TI      (XX)
```

from equation (XVII)

```
VTR(I)=G*K1*(TTR(I)-(NF-I)*TI)                            (XXI)
TS(I)=VTR(I)/(MU*G)+TTR(I)                      (XXII), (XVI)
STPOSN(I)=XTR+VTR(I)*(TS(I)-TTR(I))-MU*G/2
          *(TS(I)-TTR(I))**2                    (XXIII), (XV)
EXT(I)=STPOSN(I)-XTR                            (XXIV), (XIX)
```

Since units interact, some of the variables in the above equations will be altered, however the form will remain basically the same. The theory of collisions will now be developed.

Collisions between failed units can take place in a number of different locations, which each require a set of equations. In a two-unit collision (which is the only accepted occurrence), both units can be on the slope, one may be in a transition stage, with the other either on the slope or on the horizontal base, or finally both may be on the base. The initial problem is to determine when a collision will occur between the I and (I-1) units.

To determine the position of a unit I the value of the x component of the location of the centre of mass will be used. The y component can be easily calculated through substitution. The position at time, t, of the centre of gravity depends upon the failure time of I and the interactions which have occurred. An added factor in considering collisions between units is the importance of the transition assumption. As the center of gravity of a unit approaches XTR, the front half of the unit must be moved along the base to determine whether a collision can occur with a unit in front. Similarly, after transition, the rear half of the failure section must still be on the slope to allow for collision with the unit behind. Considering these factors then, the position of the Ith unit must be calculated for four situations:

1. While on the slope
2. While on the slope as the front of the unit moves on to the base
3. While on the base with rear of the unit on the slope
4. While on the horizontal base

First the unit I, which has not interacted, will be examined.

1. POSN(I)=x component

On the slope, before interaction.

```
POSN(I)=XAP(I)+V(I)*(T-(NF-I)*TI)*cos(TH)+K(I)
        *(T-(NF-I)*TI)**2*cos(TH)                    (XXV)
```

where V(I)=initial velocity which is zero for this case

K(I)=K1*G/2

POSN(I)=XAF(I)+K(I)*(T-(NF-I)*TI)**2*cos(TH) (XXVa)

This is developed simply from Equation X, where the x component of the travel distance is X*cos(TH)

2. On the slope after a critical position, CRP1, which is defined as the x component of the coordinate of the center of mass where the unit's front edge just touches the point, XTR.

CRP1=XTR-W/2*cos(TH)

Again, before an interaction and with initial velocity zero.

POSN(I)=XAF(I)+K(I)*(T-(NF-I)*TI)**2*cos(TH) (XXV a)

The front edge must be considered, so a position with the unit on the x-axis is assumed, such that the distance that the unit's front edge has extended past XTR, measured along the extended slope, is the value of the distance between XTR and the front edge measured along the base (See Figure # 12) From Figure # 12, the assumed position of I, ASPOSN(I) can be calculated.

ASPOSN(I)=XTR-(XTR-XAF(I)-K(I)*(T-(NF-I)*TI)**2
*cos(TH))/cos(TH)

3. On the slope before a critical position, CRP2, which is defined as the x value of the location of the center of mass where the rear edge of the unit just coincides with XTR.

CPR2=XTR+W/2

Before interaction and with initial velocity equal to VTR(I), initial position will now be XTR, since the unit is moving on the base. From equation (XIV).

POSN(I)=XTR+VTR(I)*(T-TTR(I))+K(I)*(T-TTR(I))**2 (XXVII)

where K(I)=-MU*G/2

Now, the rear edge which is still on the slope must be considered by assuming a position for the unit on the extended slope (before the x-axis) in a manner similar to situation 2 above. See Figure # 12.

ASPOSN(I)=XTR+(VTR(I)*(T-TTR(I))+K(I)*(T-SPT(I)**2)

*cos(TH) (XXVII)

where K(I)=-MU*G/2

4. On the horizontal base, no interaction; from above

POSN(I)=XTR+VTR(I)*(T-TTR(I))+K(I)*(T-TTR(I))**2 (XXVII)

where K(I)=-MU*G/2

Since these equations fit the specific case of non-interaction, equations will be developed to generalize the model application. In the situation where an interaction has occurred, the movement characteristics of the unit will change, so that a subsequent calculation of position will depend on the new parameters. To permit the generalization, a number of variables will be used which can be redefined after each collision. These terms are:

SPV(I)=Specific velocity

SPT(I)=Specific time

SPP(I)=Specific position

The equations for position contain three basic terms: the initial position, the velocity term, and the acceleration term. Generalizing the equations:

1. from (XXVa), on slope

```
POSN(I)=SPP(I)+SPV(I)*(T-SPT(I))*cos(TH)+K(I)
        *(T-SPT(I))**2*cos(TH)                    (XXIX)
   where K(I)=K1*G12
```

2. from (XXVIa), on slope, after CRP1

```
ASPOSN(I)=XTR-(XTR-SPP(I)-SPV(I)*(T-SPT(I))*COS(TH)-
          K(I)*(T-SPT(I))**2*COS(TH)/COS(TH)
   K(I)=-MU*G/2
```

3. from (XXVIII), on base, before CRP2

```
ASPOSN(I)=XTR+(SPP(I)+SPV(I)*(T-SPT(I))+K(I)
          *(T-SPT(I)**2-XTR)*COS(TH)
   K(I)=-MU*G/2
```

4. from (XXVII), on base

```
POSN(I)=SPP(I)+SPV(I)*(T-SPT(I))+K(I)*(T-SPT(I))**2
```

The equations for velocity and acceleration and other parameters can easily be developed from the same principles as the above equations. The next problem is calculating when a collision will occur. There are seven situations which require consideration, the original four, plus three situations where the front unit may have stopped before a collision occurs. Examining a collision between unit I and the I-1 unit the situations are as follows.

1. I, I-1 on the slope
2. I on base before CRP2
   I-1 on slope
2.a. I stopped on base before CRP2
   I-1 on slope
3. I on base after CRP2
   I-1 on slope after CRP1
3.a. I stopped on base after CRP2
   I-1 on slope after CRP1
4. I on base
   I-1 on base
5. I stopped on base
   I-1 on base

Collision or interaction will occur when two units' edges are in the same position, that is when the centres of mass are a distance, W, their width apart. The positions of the units, I and I-1, can be continuously calculated and there is a potential time of collision, PTC, where the unit I-1, catches up to unit I. This time of collision will be designated by a value,

PTC=PTC(I, CN(I))

where I designates a collision between I-1 and I, and CN(I) is the collision number or the frequency of collisions between the units during movement.

Utilizing the equations for POSN(I) and POSN(I-1), TC, the time of collision can be calculated for each situation.

```
POSN(I)=SPP(I)+SPV(I)*(T-SPT(I))*COS(TH)+K(I)
        *(T-SPT(I))**2*COS(TH)                              (XXIXa)
POSN(I-1)=SPP(I-1)+SPV(I-1)*(T-SPT(I-1))*COS(TH)+K(I-1)
        *(T-SPT(I-1))**2*COS(TH)
```

for collision on the slope,

```
POSN(I)-POSN(I-1)=W*COS(TH)
```

subtracting POSN(I)-POSN(I-1) and equating to W*COS(TH) gives:

```
W*COS(TH)=SPP(I)+SPV(I)*(T-SPT(I))*COS(TH)+K(I)*(T-SPT(I))
        **2*COS(TH)-SPP(I-1)-SPV(I-1)*T-SPT(I-1))
        *COS(TH)-K(I-1)*(T-SPT(I-1))**2*COS(TH)
W*COS(TH)=SPP(I)+SPV(I)*T*COS(TH)-SPV(I)*SPT(I)*COS(TH)
        +K(I)*T**2*COS(TH)-K(I)*T*SPT(I)*2*COS(TH)+K(I)
        *SPT(I)**2*COS(TH)-SPP(I-1)-SPV(I-1)*T*COS(TH)
        +SPV(I-1)*SPT(I-1)*COS(TH)-K(I-1)*T**2*COS(TH)
        +K(I-1)*T*SPT(I-1)*2*COS(TH)-K(I-1)*SPT(I-1)
        **2*COS(TH)
```

Therefore:

```
O=W-(SPP(I)-SPP(I-1))/COS(TH)+SPV(I)*SPT(I)-SPV(I-1)
  *SPT(I-1)-K(I)*SPT(I)**2+K(I-1)*SPT(I-1)**2
  +(SPV(I-1)-SPV(I)-K(I-1)*SPT(I-1)*2+K(I)*SPT(I)*2)*T
```

+(K(I-1)-K(I))*T**2

This equation is a quadratic equation of form:

A(1)*T**2+A(2)*T+A(3)=0

By finding the roots of the equation, PTC will be determined. If these times fit within a time range during which situation 1. can occur, then an interaction will result. For Situation 1. the time range is bounded by zero and TTR(I). Similar equations can be developed for each situation. In the following calculations, the algebra will not be included. Also, Situation 2 and 3 are combined, as are 2a. and 3a., since the results are the same.

Situation 1: Equation simplifies to a linear equation since

K(I)=K(I-1)=K1*G/2

Therefore,

PTC(I)=-A(3)/A(2)

Situation 2 and 3: Solving the system of equations (XXV a) and (XXVIII)

A(1)=K(I-1)-K(I)   where K(I)=-MU*G/2

K(I-1)=G/2*K1

A(2)=-SPV(I)+SPV(I-1)-K(I-1)*SPT(I-1)*2+K(I)*SPT(I)*2

A(3)=W-((XTR-SPP(I-1))/COS(TH)-XTR+SPP(I)+SPV(I)+SPT(I)

-SPV(I-1)*SPT(I-1)-K(I)*SPT(I)**2+K(I-1)*SPT(I-1)**2

PTC(I) will be equal to the roots of the equation.

Situation 2a. and 3a.: Since the unit I has stopped moving

POSN(I)=STPOSN(I)

which is not dependent upon time.

Solving using (XXX), gives:

A(1)=K(I-1)

A(2)=SPV(I-1)-K(I-1)*SPT(I-1)*2

A(3)=W-STPOSN(I)+XTR-XTR/COS(TH)+SPP(I-1)/COS(TH)
-SPV(I-1)*SPT(I-1)+K(I-1)*SPT(I-1)**2

Again, PTC(I) will come from the roots of the equation.

Situation 4: Using (XXXII) for POSN(I), POSN(I-1), gives:

A(1)=0

A(2)=-SPV(I)+SPV(I-1)-K(I-1)*SPT(I-1)*2
+K(I)*SPT(I)*2

A(3)=W-SPP(I)+SPP(I-1)+SPV(I)*SPT(I)
-SPV(I-1)*SPT(I-1)-K(I)*SPT(I)**2
+K(I-1)*SPT(I-1)**2

PTC(I)=-A(3)/A(2)

Situation 5: The unit I has stopped moving therefore its position is not time dependent. Using equation (XXXII) and STPOSN(I) gives:

A(1)=K(I-1)

A(2)=SPV(I-1)-K(I-1)*2*SPT(I-1)

A(3)=W-STPOSN(I)+SPP(I-1)-SPV(I-1)*SPT(I-1)
+K(I-1)*SPT(I-1)**2

PTC(I) will be equal to the roots of the equation.

The potential time of collision of all units can be calculated and the first one to occur will have the lowest value, within the time range of the situation. When this collision has occurred, a new set of conditions will be generated. The conditions depend on the interaction hypothesis of the particular model. The next step is to generate the equations to define the new conditions and then iterate the collision/generation procedure until the final conditions are produced.

COMPUTER PROGRAM FOR ELASTIC MODEL

```
//             JOB        (AD191190,
//   ),'MAX',MSGLEVEL=(1,1),
//   CLASS=K
//  EXEC IMSLS
//FORT.SYSIN DD *
      REAL CRP1,CRP2,CRP3,XTR,MU,TH1,W,D,L,TI,HL,H,K1,SL1,SL2,
     MRAD/.017453925/,X(20),Y(20),Y2(20),ERR1(20),AM(20,2),
     MB(20,2),XAF(20),YAF(20),
     MG,TTR(10),VTR(10),TS(10),SPP(10),SPV(10),SPT(10),
     MK(10),PATC(10),VATC(10),VAC(10),CT,A(3),CPX(2),REX(2),LOC(10),
     MPTC(10),TIC,TC(10,60),POSN(10),CN(10),CST(10),CPT(10)
     M,CPTSPP(10),CPTSPV(10),CPTSPT(10),CPTK(10),EXIT(10),CHK,TS3
     M,CSTSPP(10),CSTSPV(10),CSTSPT(10),CSTK(10),STPOSN(10)
     M,FMU,EXT(10),TH
      COMPLEX Z(2)
      INTEGER N,NDEG,IER,NF,IL1,I,MAX,COLL
      COMMON SPP(10),SPV(10),SPT(10),K(10),CSTSPP(10),CSTSPV(10)
     M,CSTSPT(10),CSTK(10),CPTSPP(10),CPTSPV(10),CPTSPT(10),
     MCPTK(10),XTR,VTR(10),TTR(10),MU,G,XAF(20)
     M,NF,TI,K1,LOC(10),CPT(10),CST(10),I,IL1
C     DEFINE PARAMETERS
      TH=25
      TH1=TH
      L=400
      D=25
```

```
      W=20
C     CHANGE DEGREES TO RADIANS
      TH1=TH1*RAD
C     CALCULATE NECESSARY PARAMETERS
      G=9.8056
      FMU=0.8
      MU=TAN(TH1)*FMU
      HL=L*COS(TH1)
      H=L*SIN(TH1)
      N=L/W
      NF=10
      TI=.5
      K1=SIN(TH1)-MU*COS(TH1)
      SL1=-TAN(TH1)
      SL2=-1/SL1
      XTR=(D/2*(1-1/COS(TH1))-H)/SL1
      CRP1=XTR-COS(TH1)*W/2
      CRP2=XTR+W/2
C     DEFINE A MATRIX OF THE CENTRE OF MASS COORDINATES
C     BY EQUATING 3. TO 6. FOR I=1 TO N
      DO 91 I=1,N
      X(I)=(D/(2*COS(TH1))+(I-.5)*W/SIN(TH1))/(SL2-SL1)
      Y(I)=SL1*X(I)+(H-D/(2*COS(TH1)))
C     CHECK THE ACCURACY OF INTERSECTION BY SUBSTITUTING
C     X IN THE SECOND EQUATION AND EVALUATING AN ERR VALUE
      Y2(I)=X(I)*SL2+(H-D/COS(TH1)-(I-.5)*W/SIN(TH1))
      ERR1(I)=Y(I)-Y2(I)
```

```
C   SET UP THE MATRIX OF X AND Y VALUES
      AM(I,1)=X(I)
      AM(I,2)=Y(I)
   91 CONTINUE
C   ASSUME A FAILURE, THEN CALCULATE THE STATE AFTER THE
C   FAILURE, ASSUMING THAT THE UNIT MOVES TO THE SURFACE
C   IMMEDIATELY ABOVE THE (I+1) UNIT
      DO 92 I=1,N
      YAF(I)=Y(I)
      XAF(I)=(YAF(I)-H-D/(2*COS(TH1)))/SL1
      B(I,1)=XAF(I)
      B(I,2)=YAF(I)
   92 CONTINUE
C   CONSIDER AN AVALANCHE OF NF UNITS, STARTING WITH THE
C   FIRST UNIT. NF IS THE FIRST UNIT TO FAIL AND THE REST
C   FOLLOW AT INTERVALS (NF-I)*TI.
C   CALCULATE THE INITIAL (NO COLLISION) VARIABLE VALUES.
      DO 40 I=1,NF
      TTR(I)=SQRT((YAF(I)-D/2)/SIN(TH1)*2/(G*K1))+(NF-I)*TI
      VTR(I)=G*K1*(TTR(I)-(NF-I)*TI)
      TS(I)=VTR(I)/(MU*G)+TTR(I)
      STPOSN(I)=XTR+VTR(I)*(TS(I)-TTR(I))-
     * MMU*G/2*(TS(I)-TTR(I))**2
   40 CONTINUE
      DO 38 I=1,NF
      CN(I)=0.
      CPT(I)=0.
```

```
      CST(I)=0.
      PTC(I)=1000.
      DO 299 J=1,10
      TC(J,CN(I))=0.
  299 CONTINUE
   38 CONTINUE
      CT=0.
      MAX=0
C     FIND POSSIBLE COLLISION TIMES FOR ALL UNIT COLLISIONS
   39 DO 41 I=2,NP
      IL1=I-1
      DO 555 I555=1,2
      Z(I555)=0.
  555 CONTINUE
      IF(CT.GE.TTR(I-1))GO TO 4
      IF(CT.GE.TTR(I))GO TO 2
      IF(COLL.EQ.I) GO TO 2
C     SPECIFY VARIABLES IF REQUIRED
      LOC(I)=1.
      LOC(I-1)=1.
      CALL PARVAL
C     SITUATION 1, FIND ROOTS. IF THEY ARE COMPLEX,
C     NO COLLISION OCCURS
    9 NDEG=1
      A(1)=-SPV(I)+SPV(I-1)-K(I-1)*SPT(I-1)*2+K(I)*SPT(I)*2
      A(2)=W-(SPP(I)-SPP(I-1))/COS(TH1)+SPV(I)*SPT(I)-
     MSPV(I-1)*SPT(I-1)-K(I)*SPT(I)**2+K(I-1)*SPT(I-1)**2
```

```
      CALL ZPOLR(A,NDEG,Z,IER)
      CPX(1)=AIMAG(Z(1))
      REX(1)=REAL(Z(1))
      EXIT(I)=1
      IF(CPX(1).EQ.0..AND.REX(1).GE.0..AND.REX(1).LE.TTR(I)
     M.AND.REX(1).GE.CT.AND.REX(1).GT.SPT(I-1).
     MAND.REX(1).GT.CT) GO TO 51
      Z(1)=0.
C     SITUATION 2/3 IS TESTED IF SITUATION 1 DID NOT RESULT
C     IN COLLISION. IF THE ROOTS ARE COMPLEX OR GREATER THAN
C     TTR(I-1) THEN COLLISION WILL NOT OCCUR.
    2 LOC(I)=4.
      LOC(I-1)=1.
      CALL PARVAL
  560 NDEG=2
      A(1)=K(I-1)-K(I)
      A(2)=-SPV(I)+SPV(I-1)-K(I-1)*SPT(I-1)*2+K(I)*SPT(I)*2
      A(3)=W-((XTR-SPP(I-1))/COS(TH1)-XTR+SPP(I))+SPV(I)*SPT(I)-
     MSPV(I-1)*SPT(I-1)-K(I)*SPT(I)**2+K(I-1)*SPT(I-1)**2
      CALL ZPOLR(A,NDEG,Z,IER)
      DO 10 I10=1,2
      CPX(I10)=AIMAG(Z(I10))
      REX(I10)=REAL(Z(I10))
      EXIT(I)=2
      IF(CPX(I10).EQ.0..AND.REX(I10).GE.0..AND.REX(I10).LE.
     MTTR(I-1).AND.REX(I10).GE.TTR(I).AND.REX(I10).LE.TS(I).
     MAND.REX(I10).GT.CT) GO TO 52
```

```
      Z(I10)=0.
   10 CONTINUE
      CRP3=CRP2+W/2
      IF(STPOSN(I).GT.CRP3) GO TO 4
      NDEG=2
      A(1)=K(I-1)
      A(2)=SPV(I-1)-K(I-1)*SPT(I-1)*2
      A(3)=W-STPOSN(I)+XTR-XTR/COS(TH1)+SPP(I-1)/COS(TH1)-
     MSPV(I-1)*SPT(I-1)+K(I-1)*SPT(I-1)**2
      CALL ZPOLR(A,NDEG,Z,IER)
      TS3=TS(I)-.3
      DO 210 I210=1,2
      CPX(I210)=AIMAG(Z(I210))
      REX(I210)=REAL(Z(I210))
      EXIT(I)=3
      IF(CPX(I210).EQ.0..AND.REX(I210).GE.0..AND.REX(I210).LE.
     MTTR(I-1).AND.REX(I210).GE.TS3.
     MAND.REX(I210).GT.CT)GO TO 811
      Z(I210)=0.
  210 CONTINUE
C     SITUATION 4 IS TESTED IF SITUATION 2/3 DID NOT RESULT
C     IN COLLISION. IF THE ROOTS ARE COMPLEX OR THE VALUES
C     ARE GREATER THAN THE TS OF I OR I-1 THEN THERE IS
C     NO COLLISION
    4 IF(COLL.EQ.I)GO TO 844
      LOC(I)=4.
      LOC(I-1)=4.
```

```
      CALL PARVAL
  561 NDEG=1
      A(1)=-SPV(I)+SPV(I-1)-K(I-1)*SPT(I-1)*2+K(I)*SPT(I)*2
      A(2)=W-SPP(I)+SPP(I-1)+SPV(I)*SPT(I)-
     MSPV(I-1)*SPT(I-1)-K(I)*SPT(I)**2+K(I-1)*SPT(I-1)**2
      CALL ZPOLR(A,NDEG,Z,IER)
      CPX(1)=AIMAG(Z(1))
      REX(1)=REAL(Z(1))
      EXIT(I)=4
      IF(CPX(1).EQ.0..AND.REX(1).GE.0..AND.REX(1).LE.TS(I).
     MAND.REX(1).LE.TS(I-1).AND.REX(1).GE.TTR(I-1).
     MAND.REX(1).GT.CT) GO TO 54
      Z(1)=0.
C     SITUATION 5 IS TESTED IF SITUATION 4 DID NOT RESULT
C     IN COLLISION. IF THE ROOTS ARE COMPLEX OR IF THE
C     VALUES ARE GREATER THAN THE TS OF I, THEN COLLISION
C     DOES NOT RESULT.
    5 NDEG=2
      A(1)=K(I-1)
      A(2)=SPV(I-1)-K(I-1)*2*SPT(I-1)
      A(3)=W-SPP(I)+SPP(I-1)-SPV(I)*(TS(I)-SPT(I))-
     MSPV(I-1)*SPT(I-1)-K(I)*(TS(I)-SPT(I))**2+
     MK(I-1)*SPT(I-1)**2
      CALL ZPOLR(A,NDEG,Z,IER)
      DO 11 I11=1,2
      CPX(I11)=AIMAG(Z(I11))
      REX(I11)=REAL(Z(I11))
```

```
      EXIT(I)=5
      IF(CPX(I11).EQ.0..AND.REX(I11).GE.0..AND.REX(I11).
     MLE.TS(I-1).AND.REX(I11).GT.CT) GO TO 55
      Z(I11)=0.
   11 CONTINUE
C     IF NONE OF THE SITUATIONS RESULT IN COLLISION, THEN THERE
C     IS NO COLLISION BETWEEN UNITS I AND I-1 UNDER THE GIVEN
C     CONDITIONS.
  844 PTC(I)=1000.
      GO TO 41
   51 PTC(I)=REX(1)
      GO TO 41
   52 IF(COLL.NE.I) GO TO 833
      CHK=((SPV(I)-SPV(I-1))*2)/((K1+MU)*G)*.9
     M+SPT(I)
      IF(REX(I10).GE.CHK)GO TO 833
      GO TO 10
  833 PTC(I)=REX(I10)
      GO TO 41
  811 IF(COLL.NE.I)GO TO 834
      CHK=((SPV(I)-SPV(I-1))*2)/((K1+MU)*G)*.9
     M+SPT(I)
      IF(REX(I210).GE.CHK)GO TO 834
      GO TO 210
  834 PTC(I)=REX(I210)
      GO TO 41
   54 PTC(I)=REX(1)
```

```
      GO TO 41
   55 PTC(I)=REX(I11)
   41 CONTINUE
      TIC=AMIN1(PTC(2),PTC(3),PTC(4),PTC(5),PTC(6),
     MPTC(7),PTC(8),PTC(9),PTC(10))
      MAX=MAX+1
      IF(MAX.EQ.75)GO TO 888
      IF(TIC.EQ.1000.)GO TO 80
      DO 61 I=2,NF
      IF(TIC.EQ.PTC(I))GO TO 62
   61 CONTINUE
   62 CN(I)=CN(I)+1.
      COLL=I
      TC(I,CN(I))=PTC(I)
      CT=TC(I,CN(I))
      IL1=I-1
      IF(TC(I,CN(I)).LT.TTR(I))GO TO 63
      IF(TC(I,CN(I)).GT.TS(I).AND.TC(I,CN(I)).GE.TTR(I-1))GO TO 82
      IF(TC(I,CN(I)).LT.TTR(I-1))GO TO 64
      GO TO 65
   63 LOC(I)=1.
      LOC(I-1)=1.
      CALL PARVAL
  766 DO 69 I69=IL1,I
      PATC(I69)=SPP(I69)+SPV(I69)*(TC(I,CN(I))-SPT(I69))*
     MCOS(TH1)+K(I69)*(TC(I,CN(I))-SPT(I69))**2*COS(TH1)
      VATC(I69)=SPV(I69)+K(I69)*2*(TC(I,CN(I))-SPT(I69))
```

```
69 CONTINUE
   CPT(I)=1.
   CPT(I-1)=1.
   VAC(I)=VATC(IL1)
   VAC(IL1)=VATC(I)
   DO 70 I70=IL1,I
   SPP(I70)=PATC(I70)
   SPV(I70)=VAC(I70)
   SPT(I70)=TC(I,CN(I))
   K(I70)=K1*G/2
   CPTSPP(I70)=SPP(I70)
   CPTSPV(I70)=SPV(I70)
   CPTSPT(I70)=SPT(I70)
   CPTK(I70)=K(I70)
   NDEG=2
   A(1)=K(I70)*COS(TH1)
   A(2)=SPV(I70)*COS(TH1)-2*K(I70)*SPT(I70)*COS(TH1)
   A(3)=SPP(I70)-SPV(I70)*SPT(I70)*COS(TH1)+
  MK(I70)*SPT(I70)**2*COS(TH1)-XTR
   CALL ZPOLR(A,NDEG,Z,IER)
   DO 71 I71=1,2
   CPX(I71)=AIMAG(Z(I71))
   REX(I71)=REAL(Z(I71))
   IF(CPX(I71).EQ.0.)GO TO 72
71 CONTINUE
72 TTR(I70)=REX(I71)
   VTR(I70)=G*K1*(TTR(I70)-SPT(I70))+VAC(I70)
```

```
      TS(I70)=VTR(I70)/(MU*G)+TTR(I70)
      STPOSN(I70)=XTR+VTR(I70)*(TS(I70)-TTR(I70))-
     MMU*G/2*(TS(I70)-TTR(I70))**2
   70 CONTINUE
      GO TO 39
   65 LOC(I)=4.
      LOC(I-1)=4.
      CALL PARVAL
  868 DO 68 I68=IL1,I
      PATC(I68)=SPP(I68)+SPV(I68)*(TC(I,CN(I))-SPT(I68))
     M+K(I68)*(TC(I,CN(I))-SPT(I68))**2
      VATC(I68)=SPV(I68)+K(I68)*2*(TC(I,CN(I))-SPT(I68))
   68 CONTINUE
      CST(I)=1.
      CST(I-1)=1.
      VAC(I)=VATC(IL1)
      VAC(IL1)=VATC(I)
      DO 66 I66=IL1,I
      SPP(I66)=PATC(I66)
      SPV(I66)=VAC(I66)
      SPT(I66)=TC(I,CN(I))
      K(I66)=-MU*G/2
      CSTSPP(I66)=SPP(I66)
      CSTSPV(I66)=SPV(I66)
      CSTSPT(I66)=SPT(I66)
      CSTK(I66)=K(I66)
      TS(I66)=SPV(I66)/(MU*G)+SPT(I66)
```

```
      STPOSN(I66)=SPP(I66)+SPV(I66)*(TS(I66)-SPT(I66))
     M+K(I66)*(TS(I66)-SPT(I66))**2
   66 CONTINUE
      GO TO 39
   64 LOC(I)=4.
      LOC(I-1)=1.
      CALL PARVAL
  967 IF(TC(I,CN(I)).GT.TS(I))GO TO 640
      PATC(I)=SPP(I)+SPV(I)*(TC(I,CN(I))-SPT(I))+
     MK(I)*(TC(I,CN(I))-SPT(I))**2
      VATC(I)=SPV(I)+K(I)*2*(TC(I,CN(I))-SPT(I))
      GO TO 641
  640 PATC(I)=STPOSN(I)
      VATC(I)=0.
  641 PATC(IL1)=SPP(IL1)+SPV(IL1)*(TC(I,CN(I))-SPT(IL1))*
     MCOS(TH1)+K(IL1)*(TC(I,CN(I))-SPT(IL1))**2*COS(TH1)
      VATC(IL1)=SPV(IL1)+K(IL1)*2*(TC(I,CN(I))-SPT(IL1))
      CST(I)=1.
      CPT(I-1)=1.
      VAC(I)=VATC(IL1)
      VAC(IL1)=VATC(I)
      DO 67 I67=IL1,I
      SPP(I67)=PATC(I67)
      SPV(I67)=VAC(I67)
      SPT(I67)=TC(I,CN(I))
   67 CONTINUE
      K(I)=-MU*G/2
```

```
      K(IL1)=K1*G/2
      CPTSPP(IL1)=SPP(IL1)
      CPTSPV(IL1)=SPV(IL1)
      CPTSPT(IL1)=SPT(IL1)
      CPTK(IL1)=K(IL1)
      CSTSPP(I)=SPP(I)
      CSTSPV(I)=SPV(I)
      CSTSPT(I)=SPT(I)
      CSTK(I)=K(I)
      TS(I)=SPV(I)/(MU*G)+SPT(I)
      NDEG=2
      A(1)=K(IL1)*COS(TH1)
      A(2)=SPV(IL1)*COS(TH1)-2*K(IL1)*SPT(IL1)*COS(TH1)
      A(3)=SPP(IL1)-SPV(IL1)*SPT(IL1)*COS(TH1)+
     MK(IL1)*SPT(IL1)**2*COS(TH1)-XTR
      CALL ZPOLR(A,NDEG,Z,IER)
      DO 73 I73=1,2
      CPX(I73)=AIMAG(Z(I73))
      REX(I73)=REAL(Z(I73))
      IF(CPX(I73).EQ.0.)GO TO 74
   73 CONTINUE
   74 TTR(IL1)=REX(I73)
      VTR(IL1)=G*K1*(TTR(IL1)-SPT(IL1))+VAC(IL1)
      TS(IL1)=VTR(IL1)/(MU*G)+TTR(IL1)
      STPOSN(I)=SPP(I)+SPV(I)*(TS(I)-SPT(I))
     M+K(I)*(TS(I)-SPT(I))**2
      STPOSN(IL1)=XTR+VTR(IL1)*(TS(IL1)-TTR(IL1))-
```

```
     MMU*G/2*(TS(IL1)-TTR(IL1))**2
      GO TO 39
   82 LOC(I)=4.
      LOC(I-1)=4.
      CALL PARVAL
  685 PATC(I)=SPP(I)+SPV(I)*(TS(I)-SPT(I))+K(I)*(TS(I)-SPT(I))**2
      VATC(I)=0.
      PATC(IL1)=SPP(IL1)+SPV(IL1)*(TC(I,CN(I))-SPT(IL1))+
     MK(IL1)*(TC(I,CN(I))-SPT(IL1))**2
      VATC(IL1)=SPV(IL1)+K(IL1)*2*(TC(I,CN(I))-SPT(IL1))
      CST(I)=1.
      CST(I-1)=1.
      VAC(I)=VATC(IL1)
      VAC(IL1)=VATC(I)
      DO 83 I83=IL1,I
      SPP(I83)=PATC(I83)
      SPV(I83)=VAC(I83)
      SPT(I83)=TC(I,CN(I))
      K(I83)=-MU*G/2
      CSTSPP(I83)=SPP(I83)
      CSTSPV(I83)=SPV(I83)
      CSTSPT(I83)=SPT(I83)
      CSTK(I83)=K(I83)
   83 CONTINUE
      TS(I)=SPV(I)/(MU*G)+SPT(I)
      TS(IL1)=TC(I,CN(I))
      STPOSN(IL1)=PATC(IL1)
```

```
      STPOSN(I)=SPP(I)+SPV(I)*(TS(I)-SPT(I))
     M+K(I)*(TS(I)-SPT(I))**2
      GO TO 39
  888 GO TO 80
   80 DO 921 I921=1,NF
      EXT(I921)=STPOSN(I921)-XTR
  921 CONTINUE
      WRITE(6,100)TH,L,W,D,N,FMU,XTR,TI
  100 FORMAT(1X,F6.2,2X,F5.1,2X,F5.1,2X,F5.1,2X,I3,2X,F4.2,2X,F10.4,
     M2X,F3.1)
      WRITE(6,101) (STPOSN(I),I=1,NF),(TS(I),I=1,10),(CN(I),I=1,10)
     M,(EXT(I),I=1,10)
  101 FORMAT(1X,'FINAL POSITIONS'//,(10(1X,F10.5,/)),//,(10(1X,F10.5/)),
     M//,(1X,10F4.0),//,(10(1X,F10.5,/)))
      STOP
      END
      SUBROUTINE PARVAL
      REAL K1,LOC,MU,K
      COMMON SPP(10),SPV(10),SPT(10),K(10),CSTSPP(10),CSTSPV(10)
     M,CSTSPT(10),CSTK(10),CPTSPP(10),CPTSPV(10),CPTSPT(10),
     MCPTK(10),XTR,VTR(10),TTR(10),MU,G,XAF(20)
     M,NF,TI,K1,LOC(10),CPT(10),CST(10),I,IL1
      DO 800 I800=IL1,I
      IF(LOC(I800).EQ.4)GO TO 801
      IF(CPT(I800).EQ.1)GO TO 802
      SPP(I800)=XAF(I800)
      SPV(I800)=0.
```

```
      SPT(I800)=(NP-(I800))*TI
      K(I800)=K1*G/2
      GO TO 800
  802 SPP(I800)=CPTSPP(I800)
      SPV(I800)=CPTSPV(I800)
      SPT(I800)=CPTSPT(I800)
      K(I800)=K1*G/2
      GO TO 800
  801 IF(CST(I800).EQ.1)GO TO 804
      SPP(I800)=XTR
      SPV(I800)=VTR(I800)
      SPT(I800)=TTR(I800)
      K(I800)=-MU*G/2
      GO TO 800
  804 SPP(I800)=CSTSPP(I800)
      SPV(I800)=CSTSPV(I800)
      SPT(I800)=CSTSPT(I800)
      K(I800)=CSTK(I800)
  800 CONTINUE
      RETURN
      END
/*
```

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