NATURAL HAZARDS OF SAN MIGUEL COUNTY, COLORADO

Report to the San Miguel County Planning Commission

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A contribution to the United States
Unesco Man and the Biosphere (MAB) Program Project 6:
Study of the impact of human activities on mountain
and tundra ecosystems

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PREFACE

INSTAAR has been conducting research in mountain geoecology in the San Juan Mountains since 1969. The northern San Juans have received special attention because Silverton became the headquarters of the San Juan Avalanche Project funded under contract INSTAAR-14-06-D-7155 from the Bureau of Reclamation, United States Department of the Interior, giving us particular responsibilities for studying avalanche phenomena in Ouray and San Juan counties. There has been a rapid growth in our knowledge, not only of snow characteristics and avalanche phenomena, but also of many aspects of the vegetation cover, climatic change, surficial geology and geomorphic processes operating today upon a dramatic and unstable mountain landscape.

Thus, as the INSTAAR NASA-PY project, involving application of remote sensing techniques to the solution of land-use problems in mountain Colorado, developed, it became apparent that the northern San Juan Mountains should provide the platform upon which the two areas of INSTAAR research should be merged. This possibility materialized through the passage of House Bill 1041 by the Colorado State Legislature in 1974 requiring that the counties make provision for mapping areas under county jurisdiction that were subject to a variety of geological (natural) hazards. This report to the San Miguel County Commissioners, therefore, is the product of extensive collaboration between State, County and University agencies and individuals. It has been financed predominantly by the NASA Grant NGL-06-003-200 to INSTAAR, but with a significant contribution by the State of Colorado through San Miguel County. Furthermore, it is one of a series; similar natural hazard reports and maps have been produced for San Juan and Ouray Counties. Also, during the 1976 summer field season, mapping will be extended to Hinsdale County and our subsequent plans call for publication of a scientific monograph dealing with the natural hazards, vegetation, climate, and geomorphic processes of the northern San Juan Mountains.

Many individuals have contributed to the research and writing of this report. However, Dr. Michael J. Bovis carried the primary responsibility of developing the map legends, testing them in terms of their applicability to both remote sensing analysis and field mapping, and of organizing and coordinating the field and laboratory team. Patrick S. O'Boyle and Rebecca M. Summer acted as research geologists and principal assistants; and extensive contributions were made by Margaret Squier throughout the project. Richard Armstrong and members of the INSTAAR San Juan Avalanche Project provided extensive advice on avalanche and snow phenomena. A provisional draft of the map legends and a preliminary map of Howardsville Quadrangle, San Juan County, was presented for review and criticism during a special workshop held in Silverton in June/July 1975. Amongst others we are indebted to Messers. John Rold and Pat Rogers, Colorado Geological Survey, and Dr. Charles Robinson, of Charles Robinson and Associates, for the advice and constructive criticism in the review process. The modified legends then became the basis for mapping all three counties. Dr. Daniel H. Knepper provided extensive editorial assistance. Mr. Joseph Vitale, NASA monitor of Grant NGL-06-003-200 has provided encouragement, advice and support to which we are especially indebted. Finally the San Miguel County Commissioners and, in particular, Mark Frauhiger and Judy McCowan, are acknowledged for expressing encouragement for our proposal from initiation to completion.

The main thrust of the INSTAAR applied mountain geoecology program is an attempt to analyze the interrelations between man and his mountain environment and to pose suggestions toward mitigation of major land-use planning problems. It is therefore appropriate to designate this report as a contribution to the United States Unesco Man and the Biosphere (MAB) Program Project 6A: study of the impact of human activities on mountain ecosystems. It is hoped that the three series of maps hereby presented to San Miguel County, together with this written explanation, will assist the County Commissioners in their task of making wise land-use planning decisions. If this is the case we will have at least partially fulfilled our obligations to them, to NASA and to the spirit of Unesco MAB.

Jack D. Ives

Jack D. Ives
Director, INSTAAR
Chairman, U.S. MAB Directorate 6A

20th May 1976

SECTION ONE

INTRODUCTION

1.1: Purpose of the Study and Use of the Report

The work covered in this report is part of a wider study of natural hazards within the San Juan Mountains conducted by INSTAAR to investigate the applications of remote sensing* technology to natural hazards research. Of equal importance is the application of the data collected on geologic and snow avalanche hazards to land-use planning decisions in San Miguel County. The study area comprises the southern two-thirds of the county and includes areas that are beset by combinations of hazards resulting from actual or potential instability in rock, soil and snow materials. The following 1:24,000 topographic maps are covered in the report: Gray Head, Horsefly Peak, Ironton, Mount Sneffels, Mount Wilson, Ophir, Sams and Telluride.

For practical reasons, geologic and snow avalanche hazards are depicted on two separate series of maps and are discussed under separate headings in Sections 3 and 4 of this report; geologic hazards are restricted to phenomena produced by rock and soil instability (Appendix 1). Separate treatment of avalanche hazards emphasizes the seasonal character of slope instability within the county, but does not preclude a joint treatment of both types of hazard on a third, Overall Hazard series of maps discussed in Section 5. This series is based on a five-fold scale of hazard that should meet the immediate needs of the county with regard to zoning. Also included in Section 5 are a set of general recommendations for land-use. The separate geologic and avalanche map series are designed to be used in conjunction with the Overall Hazard series, so that the various types of hazards present can be specified. It is anticipated that this will prove valuable in the context of hazard mitigation.

Due to the scale of mapping, all boundaries drawn on the three map series involve a certain degree of generalization, with small features omitted for the sake of clarity. Wherever possible, the specific limitations of each series are stated in the relevant sections. Therefore, the maps should be regarded as reconnaissance documents, which although ensuring a timely recognition of situations which may impose constraints on certain land-use alternatives, may not yield the desired level of information necessary for solving 'site' problems, involving areas of five acres or less. This scale of problem usually requires a detailed, site investigation of hazards as these relate to specified land-use alternatives.

1.2: Methods of Study

The term 'hazard' implies that some judgement has been made of the potential interaction between natural geophysical events, and the works of man. Indeed, Colorado House Bill 1041 defines a geologic hazard as "...a geologic phenomenon which is so adverse to past, current or foreseeable construction or

*All such indicated terms are defined in the Glossary.

land-use as to constitute a significant hazard to public safety, or to property". (Rogers et al., 1974, p.2). Accordingly, most of the material reported here relates to the mapping and interpretation of features indicative of actual, or potential instability; hazards per se can only be evaluated in terms of a proposed devlopment.

For reasons of cartographic clarity, two separate legends were drawn up for mapping geologic and snow avalanche features:

(1) Features associated with rock and soil instability, and flood inundation, including: rockfall and talus areas; rock glaciers: landslides; debris flows and debris fans; physiographic floodplains and swamps; and areas of accelerated colluvial activity, including potentially-unstable slopes (Appendix 1).

(2) Features associated with snow avalanches. For mapping purposes, starting zone, track and runout zones are not differentiated; instead, avalanche path outlines are given. Also included are potential avalanche areas, defined as timbered slopes, steeper than 60 percent (31°), above 7,000 feet elevation, that currently do not show signs of avalanching (Appendix 2).

The initial mapping of geologic and avalanche features involved photo-interpretation of high altitude color and color infrared transparencies from NASA Missions 123, Roll 59; 247, Rolls 1 and 2; and 248, Rolls 14, 16 and 20. This afforded good stereoscopic* coverage of most of the study area. Additional coverage for a part of the Mount Wilson quadrangle was obtained from U.S. Forest Service black and white prints. This photographic material enabled most of the features in both legends to be identified and mapped to a first approximation.

A compilation of data from previous geologic studies provided valuable guidance in the mapping of certain features, particularly old landslide deposits and areas of expansive soil and rock. Previous geologic work in the San Miguel County study area is discussed in Section 2.3.1. For most of the study area, there was a lack of published information on snow avalanches. However, the study of Ives et al.(1976) provided valuable information on the distribution, magnitude and probable recurrence interval of avalanches near to Ophir, in the valley of Howard Fork (Figure 1) and covered this valley as far as Ophir Loop. Background information on avalanche phenomena in the northern San Juan Mountains was provided from field experience of the INSTAAR San Juan Avalanche Project, based in Silverton. (Ives et al., 1972; Armstrong et al., 1974, 1976; Miller et al.,1976).

For the most part, features in legend (1) are produced by the free-fall*, fracture*, sliding and flow of soil and rock masses. In certain cases, the predominant process can be deduced from photographs, for example, the ridges and lobes associated with slow, 'viscous'* deformation of rock glaciers in alpine basins. Light colored swaths across talus slopes were interpreted as recent talus slides, and were differentiated from stable talus areas, where lichen growth produced a more subdued tone. Arcuate scarps produced by recent landslides were readily identified in most cases, as were hummocky ground areas associated with some of the more recent failed masses. As noted above, mapping of older landslide areas was not achieved from photo-interpretation alone. Lines associated with debris flows (=mudflow) were clearly visible as lighter swaths which in some cases, could be traced to source areas in hydrothermally-altered* zones. Fresh levées on large, recent debris flows, stood out clearly under high-power, stereoscopic viewing of aerial photographs, and were used to obtain preliminary estimates of the extent of active debris flow deposition.

In legend (2), numerous avalanche paths were identified from color infrared photography by the conspicuous absence of mature coniferous or deciduous forest cover across broad swaths. Zones of infrequent, or episodic, avalanching were identifiable from the presence of secondary regrowth of aspen or willow within predominantly coniferous stands. This enabled a rapid identification of many avalanche starting zones and tracks. The extent of runout areas could be mapped to a first approximation from the photographs, although this was not always possible due to the edaphically-controlled* absence of woody species. Concomitant with the photointerpretation of avalanche paths, potential avalanche zones were identified from topographic map analysis, using a 60 percent slope gauge.

Field checking during summer and fall of 1975 yielded valuable ground truth data to corroborate and supplement the air photograph analysis. Emphasis was placed on features which had defied resolution on the photographs, such as flow-aligned timber debris in avalanche runout areas, and more subtle evidence of avalanching, including branch trimming and impact scars on trees.

A subdivision of colluvial slopes within legend (1) was made possible by a field investigation of overburden* thickness on slopes, using roadcuts and natural exposures. Slopes with unconsolidated overburdens thicker than two meters were designated potentially-unstable. Also investigated were instances of incipient landsliding, which had been obscured by forest on the photographs.

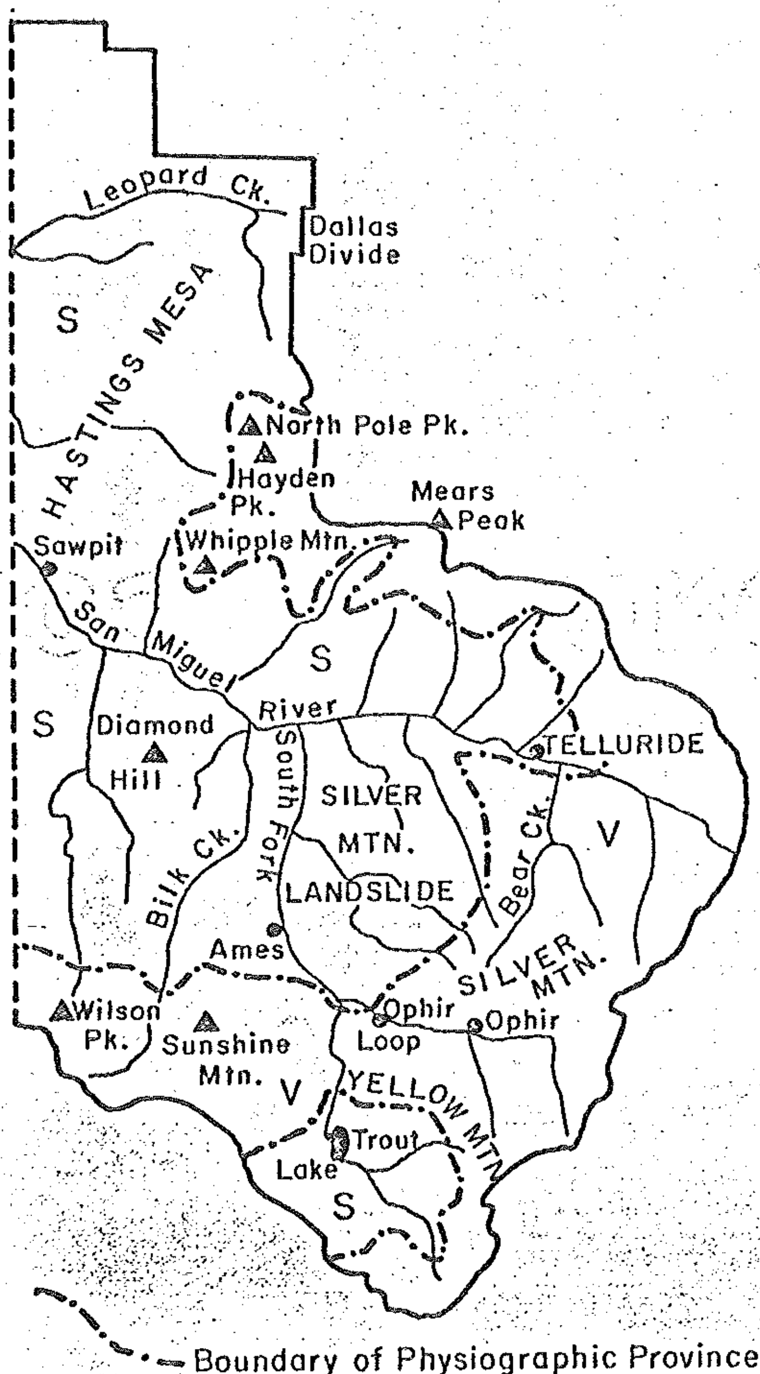

Figure 1: Physiographic provinces and major topographic features of eastern San Miguel County. Scale 1:250,000.

For explanation, see text.

ERA	PERIOD	ROCK UNITS	GEOLOGIC HAZARDS ASSOCIATED WITH ROCK UNITS AND STRATIGRAPHIC CONTACTS
CENOZOIC	QUATERNARY	Glacial and thick colluvial deposits (cst)	Unstable or potentially-unstable with respect to mass failure, in particular, where overlying impervious formations (Mancos, Morrison, Cutler).
		Landslides (ls), talus(ts) and rock glaciers(rg)	Unstable or potentially-unstable with respect to mass failure, also rockfall in (ts) and (rg) areas. Landslides may be active where overlying impermeable formations (Mancos, Morrison, Cutler).
		Debris fans(df)	Zones of potential or actual inundation from floods and drbis flows. Fans devloped peripheral to Tertiary volcanic outcrops are usually the most active.
		(NOTE: formations are not listed in sequence within the Quaternary)	
	TERTIARY	Laccolithic and stock type intrusions.	In high peaks, intrusives are rockfall areas although probably of lesser activity than Tertiary volcanic outcrops. May be associated with landslides locally, where intruded into Mesozoic shales (Mancos).
		Potosi Volcanic Group Silverton Volcanic Group San Juan Tuff	Nearly all the rock units within these three major divisions of the Tertiary volcanic material are subject to rockfall hazard and debris flow activity. Due to the rate of rockfall, large areas of talus have accumulated, with some talus sliding locally. Rock glaciers are prominent features that are probably somewhat less hazardous than steep talus slopes. The San Juan Tuff is susceptible to landsliding on a large scale, where it overlies the Mancos Formation.
		Telluride Conglomerate	A variable source of rockfall hazard, depending on the local slope angle. The Telluride is also incorporated into large landslides that have involved failure of Tertiary material across the Mesozoic Mancos Shale.
MESOZOIC	CRETACEOUS	Mancos Shale	Moderately to highly expansive soils develop, depending on local variation in types of clay minerals. Subject to mass failure, particularly where overlain by permeable or porous formations (e.g., Telluride Conglomerate, San Juan Tuff, glacial deposits, or thick colluvium). Elsewhere, mass failure is related to local hydrologic and load conditions related to intrusive laccoliths and sills.
		Dakota Sandstone	Moderate source of rockfall. Contact with underlying Morrison Formation may be unstable. Dakota areas having low to moderate slope angles present few problems.
	JURASSIC	Morrison Formation	The upper Brushy Basin Shale Member is locally moderately to highly expansive; soils are generally cohesive. The lower Salt Wash Sandstone Member is locally an active rockfall source.
		Wanakah Formation	Solution of the basal Pony Express Limestone Member of this formation can cause structural undermining of the overlying layers as rockfall.

Figure 2: Stratigraphic column and geologic hazards.

ERA	PERIOD	ROCK UNITS	GEOLOGIC HAZARDS ASSOCIATED WITH ROCK UNITS AND STRATIGRAPHIC NTACTS
MESOZOIC	JURASSIC	Entrada Formation	Moderate to high level of rockfall activity.
	TRIASSIC	Dolores Formation	Moderate to high level of rockfall activity. Gliding of blocks across the surface of the underlying Cutler Formation may take place also.
PALEOZOIC	PERMIAN	Cutler Formation	Moderate to high level of rockfall activity, depending on local stratigraphy and slope angle. Locally, gliding of resistant sandstone and and conglomerate units occurs across interbedded shale and siltstone units, at a rate dependent on local dip angle and groundwater conditions. Soils are moderately expansive in places.

Figure 2: (continued)

SECTION TWO

GEOGRAPHIC SETTING AND GEOLOGIC BACKGROUND

2.1: Regional topography

Two major physiographic provinces are recognized within the study area depicted in Figure 1. The first, denoted by 'V', is underlain principally by Tertiary* volcanic and intrusive* rocks and forms the most rugged and upstanding area in eastern San Miguel County. Large tracts of this type of country form the areas of Silver Mountain, Yellow Mountain and many peaks which demarcate the northern border with Ouray County; for example, Mears Peak, Hayden Peak and North Pole Peak. A combination of steepness of terrain and rapidity of weathering of the volcanic and intrusive material renders the volcanic province highly unstable over large areas. Additional hazards derive from snow avalanches, since large areas of the province extend above timberline and are subject to considerable snow accumulation in winter. (Plate 1).

The second major physiographic province is denoted by 'S' in Figure 1, since it is underlain by sedimentary formations* of Paleozoic* and Mesozoic* age. These give rise to a flat to undulating plateau type of country, deeply dissected by the principal streams draining the area, and contrasting markedly in its overall geologic stability when compared with the Volcanic province. Examples of topographic features within this province are Sunshine Mesa, Wilson Mesa, Deep Creek Mesa and, in the northwest part of the study area, Hastings Mesa. Since the regional direction of dip in the sedimentary rocks is to the west, Paleozoic* rocks, represented by the Permian* Cutler Formation, are restricted to the eastern part of the study area, with successively younger Mesozoic* rocks occurring to the west. The more resistant formations are exposed in rocky cliffs along the San Miguel River, principally, the Cutler, Dolores, Morrison and Dakota formations. However, the Mancos Formation underlies most of the Sedimentary province since it forms most of the dissected mesa country described above. Also, the Mancos Shale* has a large outcrop in the vicinity of Trout Lake. (Plate 2).

The physiographic form and geologic stability of the Sedimentary province can only be understood by considering the properties of this thick shale formation, together with its relationship with the overlying Tertiary volcanic formations (Figure 2). A considerable amount of landsliding has occurred at the contact* between these two rock units, the most spectacular examples being the Silver Mountain Landslide, southwest of Telluride, and the Yellow Mountain Landslide, just to the northeast of Trout Lake. The combination of an upper, permeable unit and a lower, impermeable shale has caused extensive landsliding. Landslide deposits in these situations usually consist of a mixture of tuff* material, glacial drift* and shale. This suggests that the most widespread period of landsliding occurred soon after the glacial epoch, although several phases have probably taken place in post-glacial* time and the chronology of events is not known in detail.

2.2: Effects of the Pleistocene* glaciation

A classic description of the sequence of glaciations which affected the study area and the adjacent areas in Ouray and San Juan counties is given by Atwood and Mather (1932). Glacial overdeepening of pre-glacial valleys by valley glaciers during the Pleistocene Period produced steep slopes, which in many cases were mantled by a thick layer of glacial material. In post glacial times, this combination of circumstances has probably produced the largest landslide features in the County (e.g., Silver Mountain and Yellow Mountain). Within the Volcanic province, glacial erosion carved out large cirque* basins, surrounded by sharp peaks produced by intense frost weathering during the glacial epoch. These constitute some of the most spectacular, and hazardous, features in San Miguel County, for example, Ajax Mountain, Silver Mountain and Hayden Peak.

Although the macro-relief of the Volcanic province owes its form to the direct erosional effects of moving ice during several phases of glaciation, subsequent modification of the glacial topography has occurred in post-glacial time. Large quantities of rock debris, weathered from volcanic outcrops in particular, are contained in talus deposits, rock glaciers, debris fans, physiographic floodplains and colluvial slopes. Many of these features are still evolving today and are, therefore, zones of high geologic instability from rockfall, talus sliding, debris flow activity and floodplain development. These comments also apply to the landslide areas, since although their initiation was due primarily to conditions which prevailed immediately following the last glaciation, many pockets of instability remain today, related to subtle combinations of groundwater, lithology* and geologic structure*.

2.3: Stratigraphic* and structural background

2.3.1: Previous studies of the local and regional geology.

A good regional account of the geologic history and stratigraphy of the entire San Juan region is given by Larsen and Cross (1956). At the same map scale of 1:250,000, part of the study area is covered by the later work of Steven et al.(1974) in their geologic map of the Durango 2^{o} quadrangle.

Coverage at the scale of 1:62,500 is provided by the much earlier studies of the Telluride and Ouray Folios by Cross et al. (1899, 1907). Although the regional stratigraphy has been revised considerably since these studies were completed, the Folios are, nevertheless, eminently readable from the standpoint of the modern geologist. Much of the area covered by the Folios has since been mapped at the much larger scale of 1:24,000 as part of the U.S.G.S. Geological Quadrangle Map (GQ) series: the Telluride quadrangle map of Burbank and Luedke(1966); Gray Head in preliminary form, by Bush et al.(1961); the Ironton quadrangle map of Burbank et al.(1964); and the Mount Wilson quadrangle study of Bromfield (1967). In addition, most of the Ophir quadrangle that lies within San Miguel County is covered by the study of Vhay(1962). Peripheral to the main study area, additional studies at a scale of 1:24,000 are the Placerville quadrangle study of Bush et al.(1959), the Little Cone quadrangle work of Bush et al.(1960) and the Dolores Peak quadrangle study of Bush and Bromfield(1966).

More detailed studies of specific problems or small areas are provided by the landslide study of Varnes(1949) and the commissioned studies of Chen and Associates (1974) and Western Engineers Inc.(1972, 1973). From previous INSTAAR involvement in San Miguel County, an in-house publication on the debris flow hazard along Cornet Creek is notable (Mears et al.,1974). Also, the conclusions of the studies by Sharpe(1974) and Clark(1974) concerning debris flow genesis and recurrence interval are broadly applicable to the County area.

The recent landslide maps prepared by Colton et al.(1975) for the Durango and Montrose 2^{o} sheets (scale, 1:250,000) provide useful information on the approximate location of major landslide features for areas of the County not covered by more detailed geologic studies (e.g., the areas on the Sams and Horsefly Peak quadrangles). The maps provide fairly broad guidelines in this respect, since rock glaciers and talus deposits are included in the general category 'landslide', yet these are treated as separate features in the legend used in this study (See Appendix 1).

2.3.2: Stratigraphy and lithology

Due to the considerable thickness of Paleozoic and Mesozoic sedimentary formations in the study area, coupled with the pattern of subsequent erosion of this rockpile, Precambrian* rocks are not exposed in the eastern County area, although they appear further to the east in San Juan and Ouray counties. The oldest rocks in the area belong to the upper Paleozoic Cutler Formation, which is well exposed along Bear Creek and the San Miguel River valley and gives rise to the distinct, ledged cliffs of red shale, sandstone and conglomerate*. The shale members within the Cutler are probably moderately expansive and the interbedded sandstone and conclomerate layers are, locally, active to moderate sources of rockfall.

The overlying Dolores Formation, of Triassic* age, is of similar color and composition to the Cutler Formation, consisting of interbedded shale, siltstone, sandstone and conglomerate, with a limestone unit at the base of the Formation. As might be expected, the Dolores Formation is beset by the same types of instability that occur in outcrops* of the Cutler Formation.

The Jurassic period began with the deposition of the Entrada Sandstone, a distinctive light-colored sandstone formation that forms cliffs along the San Miguel Valley from the Pandora Mill to the hamlet of San Miguel, west of Telluride. Like the underlying Dolores Formation, the Entrada is an active rockfall area (Figure 2). The Entrada is succeeded by the Wanakah Formation, divisible into a lower Pony Express Limestone Member, a middle Bilk Creek Sandstone Member and an upper member consisting of shale, siltstone and thin sandstone units. Solution of the basal limestone member causes structural undermining of the sandstone member, which in turn, leads to rockfall activity not only along the San Miguel Valley, but also along the margins of Sunshine Mesa and Wilson Mesa. Jurassic deposition came to a close with the thick Morrison Formation, exposed in steep slopes which lie above the rockfall cliffs of the Dolores, Entrada and Wanakah formations in the San Miguel Valley. The lower Salt Wash Sandstone Member of the Morrison is locally an active rockfall source. The overlying Brushy Basin Shale Member is composed of red to green mudstones, interbedded with fine-grained sandstones. Lenses of highly expansive clay occur within the mudstone units, making expansive soil a possible hazard on these slopes. Due to a lack of stratigraphic information at this scale, the precise location of these highly expansive lenses and horizons is not known precisely; therefore, they are not identified as separate units on the geologic hazard maps.

The Cretaceous* Period opened with the Dakota Sandstone, recognized by its light-colored cliff-forming units, that often give rise to rockfall activity on steep slopes. The Cretaceous closed with the accumulation of the thick Mancos Shale Formation, which attains a thickness of about 2,500 feet in the study area. Its considerable thickness and low westerly dip angle explains the large areas underlain by this formation, as noted above in the discussion of the Sedimentary physiographic province. It is remarkably homogeneous both vertically and laterally, although a few sandstone and limestone bands occur. It usually does not form rocky outcrops, due to its low mechanical strength and rapid rate of weathering. The highly fissile character of the Mancos Shale is shown in Plate 5. Usually, it weathers to a cohesive soil that often displays polygonal shrinkage cracks, indicative of moderate expansive activity(Plate 6).

The Tertiary Period opened with the deposition of the Telluride Conglomerate, comprising siltstone, sandstone and conglomerate units. The Conglomerate attains nearly 1,000 feet in thickness on the steep slopes, high above the San Miguel Valley, and gives rise to rockfall hazard above the Pandora Mill and along Bear Creek. Locally, landsliding has occurred across the underlying Mancos Shale. As with the underlying sedimentary formations, the outcrop of the Telluride Formation is completely masked by landslide deposits in the Silver Mountain Landslide area southwest of Telluride.

The bulk of Tertiary deposition occurred as volcanic tuffs, breccias and flows, the principal formations being (in stratigraphic sequence, from oldest to youngest): the San Juan Formation, which has the largest outcrop of all the volcanic formations; the Picayune Formation, Eureka Tuff, Burns Formation and Henson Formation, most of which are named by type areas in San Juan and Hinsdale counties, where most of the volcanic formations attain maximum thickness. As Figure 2 indicates, the formations younger than the San Juan Tuff comprise the Silverton Volcanic Group (Varnes, 1963), although from the standpoint of geologic hazards and stability, the entire sequence of volcanic formations can be treated as a fairly homogeneous unit. It should be noted, however, that vertical and lateral variation has been mapped in some detail (Varnes, 1963; Burbank and Luedke, 1966, 1969). The highest peaks in the eastern and northern County areas are underlain by the Gilpin Peak Tuff, for example, St. Sophia Ridge and Silver Mountain. Compared with the underlying volcanic formations, the Gilpin Peak Tuff gives rise to a large number of resistant, rocky ledges, which are very active sources of rockfall, and in some cases, debris flow activity (Plates 1, 7 and 8). However, rockfall and debris flow activity is fairly typical of most of the Tertiary volcanic outcrops (Plates 7 and 8).

Quaternary* surficial deposits*, including glacial material, debris fans, floodplain alluvium and colluvial accumulations are inextricably involved with many geologic hazards in the County area, and a discussion of these formations is postponed until Section 3. The listing in Figure 2 is not in stratigraphic sequence of deposition for Quaternary material.

2.3.3: Structural history

The major structure in the study area is the San Juan Monocline, which dates from the Laramide Orogeny*, during which the entire San Juan region was formed into a dome. The orientation of the monoclinal, or single-limbed fold* is such as to impart a steep westerly to northwesterly dip to Cretaceous and Jurassic rocks (principally) and it is thought that this situation may have caused the San Juan Tuff and Telluride Conglomerate, together with later Tertiary formations, to slide over the underlying Mancos Shale, creating the extensive landslide deposits of Silver Mountain in particular. This observation demonstrates that this type of landslide cannot be understood without reference to the structural and stratigraphic history of the area, as well as the climatic fluctuations of the Glacial Epoch.

The geometry of the monoclinal flexure, and other minor folds and faults* of Laramide age is displayed in the Paleozoic and Mesozoic outcrops along the San Miguel Valley.

The Tertiary Period also witnessed large-scale igneous* intrusive activity, in addition to the extrusive, volcanic formations already described. In some cases, these masses, intruded into Mesozoic sediments and Tertiary volcanic rocks, are partly exhumed as small laccoliths* and sills*, particularly within the area of Hastings Mesa. Elsewhere, very large intrusive bodies form high mountain areas, for example, the San Miguel Range, which includes Black Face, Sunshine Mountain and Wilson Peak, and, on a smaller scale, intrusions which lie just north of Campbell Peak, on the northern County border. From the standpoint of geologic hazards, these large intrusions are similar in character to the Tertiary volcanic outcrops, in that they are active rockfall areas. The degree of mudflow activity, however, appears to be somewhat lower on the intrusive outcrops, due probably to the slower rate of weathering of coarse, crystalline rocks, compared to friable tuffs and ash deposits. Small laccoliths intruded into the Mancos Shale often have a disruptive effect in that they are seepage lines within an otherwise impermeable shale formation. For this reason, small landslides have occurred in these locations, for example, on Hastings Mesa. The same pattern of slope failure peripheral to small intrusive bodies is also noted in southern Ouray County.

During the middle and later part of the Tertiary Period, extensive hydrothermal alteration* of (principally) Tertiary volcanic formations took place, and led to mineralization of fissures. Discussion of the economic significance of this series of events is beyond the scope of this report, yet the alteration of volcanic rocks has implications for geologic hazards also. Chemical alteration of the volcanic rock has given rise to weaker zones, which weather very rapidly compared to, say, unaltered intrusive areas. This creates large areas of unstable or potentially-unstable rock and weathered debris in high, alpine basins (e.g., along St. Sophia Ridge, above Telluride, and along much of Silver Mountain, above the valley of Howard Fork). Often, these are notable starting zones for debris flows and talus slides (q.v.) (Plates 7 and 8). It is likely , therefore, that the incidence of hydrothermal alteration may be a more important determinant of geologic instability than original differences in the structure and lithology* of the Tertiary volcanic formations. Altered areas are usually recognizable as reddish or yellowish zones, produced by hematite* and limonite* coloration.

SECTION THREE

GEOLOGIC HAZARDS

3.1: Introduction

The purpose of this section is to describe the legend used in the mapping of features associated with rock and soil instability and flood inundation. As noted earlier, the categories in this legend are not strictly speaking, hazard categories, since this concept cannot be divorced from considerations of the potential for interaction with the features of human occupance. However, the categories do specify various levels of geologic instability and from a geologic standpoint, are genetic, in that the origin of features and the predominant processes involved are implied; for example, rockfall, debris flow, physiographic floodplain. It should also be realized that most of the categories in the legend refer to readily identifiable features in the landscape, such as rock glaciers, talus slopes, landslides and debris fans. This property of the legend reflects not only mapping considerations but also emphasizes processes, a factor of considerable importance in the mitigation of hazards.

Two other features of the geologic legend should be stressed. First, only the most limiting hazard is designated in a particular area. For example, it is likely that many active landslide areas are also zones of colluvial activity, yet the mass-failure property is obviously the most limiting condition; similarly, areas of moderate colluvial activity on shale formations are mapped as expansive soil. Secondly, hazard areas should not be interpreted without reference to their local context; a sudden transition from rockfall, to moderate colluvial activity, for example, should be viewed with caution, particularly close to the boundary between the two categories. On the other hand, a change from expansive soil to moderate colluvial activity involves a much less abrupt transition. Nevertheless, any boundary should be interpreted as a zone of transition, rather than as a line across which conditions change abruptly.

3.2: Geologic hazard legend

The mapping categories are discussed below in the same order as in the legend (Appendix 1). All abbreviations refer to those used in the appendix (e.g., rf for rockfall) and are the same as those used on the geologic hazard maps.

3.2.1: Rockfall (rf)

Rockfall is the free-fall*, rolling and sliding of rock fragments after physical and chemical weathering have reduced the cohesion* and frictional contact between large blocks exposed in a cliff face. Isolated blocks fall, therefore, when gravitational stress exceeds the resisting forces of cohesion and the external friction between the block and its parent formation. Repeated freezing and thawing of water in rocky fissures may cause large blocks to become loosened, and water moving along joints in bedrock serves to decrease the friction between individual blocks. Also, chemical solution or stream undercutting of a non-resistant cliff forming rock unit may lead to structural failure and consequently, rockfall activity.

Rockfall sites may be identified in the field by the presence of a steep, jagged rock face, usually fractured or jointed, below which a talus deposit may exist. The freshness and extent of the talus material will be related to the rate of mechanical and chemical weathering of the rock debris and the rate at which rockfall activity takes place.

The steep slope north of Telluride, underlain by the Cutler, Dolores, Entrada and Wanakah formations is an active rockfall area, and this succession of rock units gives rise to similar activity between Keystone and Placerville in the San Miguel Valley (Plates 3 and 4). The Tertiary intrusive body of the Ophir Needles is also an active rockfall area, and has given rise to large talus deposits in Howard Fork valley. As noted previously in the sections on stratigraphy and structure (Section 2), most of the high Tertiary volcanic and igneous rock areas are active rockfall zones that have produced considerable talus accumulations and rock glaciers (Plates 1, 7 and 9).

3.2.2: Rock glacier (rg)

Rock glaciers consist of thick accumulations of unstable to potentially-unstable talus material within alpine basins that either cover an old, stagnant ice core, or possess large amount of interstitial ice. They are probably unconsolidated, and, therefore, susceptible to mass failure*, particularly if the ice core melts due to excavation or rapid erosion of overlying talus.

Distinct lobate tongues of rock glacier material show up well on the aerial photographs (Plate 1) and most features display a hummocky surface, traversed by pressure ridges (Plate 9). The surface material of some rock glaciers may be fairly stable, as indicated by a heavy lichen cover.

Because of the lesser rate of melting of interstitial ice and a buried ice core on north-facing slopes, the most spectacular rock glaciers are found on slopes of this orientation, examples occuring on the north face of Silver Mountain, above Alta Lakes, and the north face of Campbell Peak. However, to counter this assertion, some do occur on south-facing slopes also, for example, the feature depicted in Plate 1, on the west flank of Dallas Peak, in the headstreams of Mill Creek.

3.2.3: Landslide (ls)

A landslide results from a downward and outward movement of relatively dry mixtures of rock and soil debris, in response to external forces acting tangential to a slope. Failure occurs when a change in equilibrium takes place between gravitational stress and the slope properties of shear* strength, cohesion and internal friction. Man-induced disturbances may lead to landsliding, and include: (1) Addition of earth material to a potentially-unstable slope, thereby increasing the total load imposed on the slope material; erection of a structure may have the same effect. (2) Removal of material from the toe area of a slope by excavation or accelerated stream erosion, which creates an imbalance between the forces driving the soil layer downhill and those opposing this motion. (3) Irrigation or septic tank operation, which reduce the cohesion of the potentially potentially-unstable mass, in addition to increasing the total load imposed on the slope material.

Failure usually takes place along a recognizable surface of rupture, with the basal part failing in shear, and the upper headwall material failing in tension (Plates 10 and 11). Translational* and rotational* types are recognized, the latter having curved failure surfaces, concave upward, and involving downward motion as well as backward rotation of the slide mass, the translational type involving lateral movement, with little rotation. In the case of recent failed masses, it may be possible to deduce the type of failure, yet for older deposits (e.g., the Silver Mountain Landslide) this may be much more difficult to demonstrate. It is likely that both types of failure have occurred at various intervals to produce landsliding on this scale.

Both the rotational and translational types can involve deformation of the mass as a rigid body, revealed by the presence of several large, intact blocks of debris comprising the failed mass. Flow usually occurs to some degree however, particularly in cohesive soil areas (i.e., derived from the Mancos Shale and similar argillaceous* formations). Flow involves an internal deformation of all elements, usually accompanied by a certain amount of shearing along discrete failure planes. Both types of motion produce hummocky terrain within the failed area, which may be poorly drained as a result. Although weathering and erosion may subsequently reduce the prominence of these classic features of landslide terrain, a subdued, hummocky surface usually persists for a considerable period of time following failure (Plate 2).

In eastern San Miguel County, glacial deposits may be subject to landsliding, particularly where they overlie impervious formations such as the Morrison and Mancos. Thick accumulations of glacial material are not differentiated texturally from thick colluvial accumulations (See Section 3.2.7.1), and in fact both behave in roughly the same way, especially when water-saturated above impervious shale. Small-scale rotational slumping of glacial material overlying shale has occurred on the north-facing slope, directly south of Society Turn and on Hastings Mesa, near to the Last Dollar Road (Plate 10). Numerous pockets of instability exist within the area mapped as landslide on the Telluride geological quadrangle map of Burbank and Luedke(1966), with the most active scarps being mapped with a toothed symbol on the geologic hazard maps. In the case of the Silver Mountain Landslide, repeated failure has led to the accumulation of a considerable thickness of material, probably in excess of 500 feet in places. Rapid revegetation of the landslide area with aspen (Plate 2) means that details of the stratigraphy of the deposit are obscured, sections being rarely encountered. The roadcut along Highway 145 (Plate 12) gives some idea of the type of material involved in the landslide. The slope is decidedly unstable on its slip face, and deeper-seated movement appears to be taking place, evidenced by frequent disruption of the asphalt surface of the road overlooking Ames. The Ames Landslide, located on the opposite side of the South Fork of the San Miguel from the Silver Mountain feature, is shown in the upper left area of Plate 2. Here, slope failure is probably related to groundwater hydrologic disturbances induced by a large laccolithic intrusion into the Mancos Shale (Varnes, 1949).

3.2.4: Expansive soil and rock (es)

Expansive soil and rock contain a high percentage of clay minerals that undergo marked volume changes during cycles of wetting and drying. The most expansive clay minerals are montmorillonite* and illite* (Buckman and Brady, 1969), the former being by far the most expansive. Clay minerals have a sheeted structure and unique electrical properties that determine their behavior when in contact with water (Terzaghi and Peck, 1967). The flat surface of each clay particle carries a negative charge, which causes adsorption of water and consequent swelling of clay-rich soils.

Expansive soil in San Miguel County is almost exclusively derived from the Mancos Shale and the Morrison Formation. The much older shale in the Cutler Formation is only slightly to moderately expansive. Local concentrations of montmorillonite within the Mancos Shale may be as high as 30 percent of total volume (Bush et al., 1959) and, therefore, would be classed as highly expansive, since a sample of pure montmorillonite (also called bentonite) can expand up to 15 times its air-dry volume when wetted. Expansive soils are most readily recognized by polygonal shrinkage cracks (Plate 6) in addition to a puffy texture in the upper soil layers. The report of Western Engineers Inc.(1972) noted the presence of expansive layers within the Morrison Formation (Brushy Basin Shale Member) on the north side of the San Miguel Valley.

3.2.5: Talus slopes (ts)

A talus slope is an unstable or potentially-unstable accumulation of rock debris derived from repeated rockfall activity (Plates 1, 4, 7 and 9). Each talus slope maintains a characteristic longitudinal gradient related to the friction between rock fragments, and textural variations may occur as a response to sorting during the motion of particles across the talus slope. Coarse particles possess greater momentum, and since they are larger than the mean roughness elements on the talus slope, roll the greatest distances downslope, a process known as 'fall sorting'. Long, unbroken cliff faces produce planar talus slopes, although locally, talus cones may develop where rock debris is funneled down a gully in the cliff face(Plate 4). As noted previously, the igneous intrusion which forms the Ophir Needles is flanked by large talus accumulations, and an extensive apron of talus occurs east of Telluride, below Ingram Falls. Elsewhere, along the San Miguel Valley, less intense cases of rockfall activity give rise to slight talus development, consisting of a few scattered blocks on a slope. However, due to their proximity to existing dwellings, and, possibly proposed developments, these areas may pose a much greater threat than the much more unstable talus accumulations within high, alpine basins. This reiterates the point made in Section 1.1 and again in Section 3.1 that hazards can only be evaluated in terms of an interaction between hazardous instability and the works of man.

Many talus slopes are also zones of deposition for debris flows; from a textural standpoint, therefore, talus slopes are composite features. A gradation in form occurs between talus slopes, through talus cones, to debris fans, although for reasons of cartographic clarity, the intermediate talus cone form is not mapped as a separate category on the geologic hazard maps.

3.2.5.1: Talus slide (tss)

Most alpine basins in the study area are unstable from rockfall and debris flow activity, although locally, a higher level of hazard may exist from mass-failure* of talus material as a talus slide. This probably occurs as an adjustment of the talus toward its natural angle of repose*, perhaps in response to a locally accelerated rate of rockfall. Slides are usually identifiable as tongue-shaped projections of fresh debris beyond the toe of a talus slope, and disturbed debris within the zone of sliding often has a lighter tone, if it occurs within an otherwise stable, lichen-covered talus formation. Some talus slides have transverse pressure ridges, similar to those found on rock glaciers, although generally of much lesser relief than the latter. As noted with talus slopes, talus cones and debris fans, a gradation in forms is recognizable between talus slopes, talus slides and rock glaciers from the standpoint of pressure ridges. It is likely that ridges on talus slides are a result of a local, discrete shear failure of talus material, whereas on rock glaciers they may be due to shearing and melt subsidence, produced by wastage of an ice core.

A good example of a talus slide occurs on the south slope of Iron Mountain, just below peak 12,747. Also, some of the talus material depicted in the high basins in Plate 1 has undergone talus sliding, above the area of the rock glaciers.

3.2.6: Debris fan (df)

Debris fans accumulate in a concentrated zone at the intersection of a tributary with a major stream or valley from repeated deposition by debris flows and intermittent streams (Plates 13 and 14). Once loose debris starts to accumulate, infiltration of water from subsequent events promotes deposition in the same zone. Most flows carrying debris follow the local fall-line, thereby producing a fan-shaped deposit with a slightly convex cross-profile. It should be reocgnized that debris flows can be deflected to any part of a fan, often taking a course which deviates appreciably from the line of maximum gradient. Nearly all debris fans in the San Juan Mountains have recent debris flow deposits on their surfaces (See section 3.2.6.1) - a testimony to the present-day importance of debris flow activity as opposed to stream flood deposition. This is thought to be due to the effects of sudden thundershowers within alpine basins which contain large quantities of unstable talus and other regolith material.

Debris fans are of particular interest to the planner since often, they provide the only suitable construction sites in otherwise steep, unstable terrain. Unless they bear recent signs of debris flow activity, or flood scars, the intrinsically hazardous nature of these features may not be appreciated. The frequency of debris flow events obviously varies among fans, and must be related in some way to the amount of metastable material in the catchment basin above. Caine (1976) and Sharpe (1974) give estimates of the return period for extreme alpine events.

It should not be assumed that fans bearing no signs of recent debris flow deposition are 'safe'. A timely reminder that seemingly inactive debris fans can be affected by events of catastrophic magnitude is provided by the two inundations of the Telluride fan by Cornet Creek in 1914 and 1969. The 1914 event was by far the worst of the two and resulted in extensive structural damage to the town of Telluride (Plate 15). The natural channel of Cornet Creek across the fan has been artificially diverted from its former position on the east side of the debris fan to a location close to its present position on the west side of the fan. The debris flow of 1914, which occurred during a very heavy summer downpour, started in the upper part of Cornet Creek, close to the old Liberty Bell Mine, and descended over 2,000 vertical feet to the debris fan apex. The first slugs of the flow plugged the artificial channel, after which the flow breached the diversion dam and flowed unpredictably across a segment of the fan, which previously, had borne no recent signs of deposition. Extensive damage was sustained by buildings in this sector (Plate 15).

Cornet Creek heads into an extremely unstable alpine basin, filled with talus material. That it has been an active zone of debris flow activity over a prolonged period can be deduced from the size of the debris fan on which the town of Telluride is constructed. By contrast, many other fans developed along the San Miguel Valley are much flatter, and bear little or no signs of recent debris flow activity. Generally, the plateau areas above these fans are not sufficiently unstable to generate large flows on a regular basis (e.g., Owl Creek). The bulk of present deposition on these features is probably from sheetwash, which could mean that the fans are relict features from a more geologically active past. Alternatively, they are still 'active', but large events have a very long return period (Plates 3 and 13).

3.2.6.1: Debris flows

A debris flow is a rapid, downslope movement of a 'viscous'* mass of fine- to coarse-grained debris which has become fluidized by the entrainment of water. Most flows are thought to originate as small landslides in unstable catchment basins during intense summer thunderstorms, and usually are confined to a pre-existing channel (Sharp, 1974; Clark, 1974) although, as noted in the previous section, their trajectories may be somewhat erratic across a debris fan. Unlike floods in river channels, debris flows are extremely short-lived, though nonetheless hazardous for that reason. Unfortunately, there are very few recorded cases of flows in motion, so that the characteristics of flow must be deduced indirectly from depositional evidence on fans (Plates 8 and 13).

The lowest velocities of flow seem to occur at the edges of the flowing mass, since frictional retardation will be greatest there. This leads to the deposition of material as levées, or linear ridge-like features which usually occur as the series of overlapping, interlaced deposits produced by superimposition of successive debris flow events. The moving mass comes to a halt due to seepage of entrained water and to the shearing of debris across the fan. The abrupt slope at the terminus of most debris flows suggests a finite yield strength* for the material; therefore, the central part of the flow, at least, can then be treated as a rigid plastic body , with 'viscous' deformation occurring on the underside and margins of the flow (Johnson, 1970).

3.2.7: Colluvial slopes (cst, csa, csm, csi)

The weathering of bedrock material over prolonged periods of time leads to the production of a soil mantle. Due to the influence of raindrop impact, frost heave, runoff, animal burrowing, and gravity, amongst others, the soil mantle moves downslope. These processes are complemented by the less obvious deformation of the entire thickness of the soil mantle by the process of creep*, at a rate which usually increases with water content. Slopes which are dominated by this type of activity are termed colluvial. Strictly speaking, nearly all slopes could be classed as colluvial, but in terms of this study of hazards, only those which lack more limiting hazards, such as landsliding, talus development, etc., are classed as colluvial. The net effect of the agencies listed above is downslope motion of the soil mantle, although on any given slope, the relative importance of surficial processes (sheetwash,* raindrop impact) versus bulk processes (frost heave, creep), will vary. In many instances, colluvial processes lead to a thickening of the soil mantle downslope, producing a wedge-shaped deposit. Sub-categories are recognized here on the basis of overall thickness of material, that is, greater than or less than about six feet, in addition to relative degree of colluvial activity (Appendix 1).

3.2.7.1: Slopes with thick colluvial or glacial overburdens (cst)

Although not associated with a particular landform, as was the case for debris fans and rock glaciers, this is an extremely important category in the mapping legend, since large areas of the county have colluvial or glacial overburdens which exceed six feet in thickness. For textural reasons, colluvium is not differentiated from glacial deposits, since it is likely that all ice-contact deposits have suffered not only colluvial action, but also some unspecified level of mass-failure in post-glacial time.

Many (cst) areas are found on sedimentary or volcanic formations that weather very rapidly; for example, the Cutler, Mancos and San Juan formations. All of these areas are potentially-unstable; indeed, small slumps along roadcuts which traverse (cst) areas provide a valuable guide to the state of local stability (Plate 12). In many instances, slumps have occurred along lines of natural groundwater seepage - a timely warning of the potential impact of uncontrolled irrigation, drainage diversion and septic tank operation.

Most commonly, (cst) material exists where glacial drift and other unconsolidated deposits derived from glacial depisition occurs as unstratified masses, comprising all size grades from clay through to boulders. These deposits are particularly unstable where they overlie impervious clays or shale members of the Cutler, Morrison and Mancos formations. In these situations, the surface of the deposit may appear hummocky and irregular, indicating possible mass movement in the past. Therefore, there exists a gradation in form between (cst) areas that do not possess enough landslide features to be classed as such, and classic landslide areas, containing obvious signs of recent failure. In any event, the potentially-unstable situation of thick glacial or colluvial mantles means that (cst) material usually does not mantle very steep slopes (i.e., erosion or mass failure has already taken place, thereby 'removing' the hazard).

Finally, (cst) deposits may contribute to rockfall hazard, when large boulders embedded in a finer matrix roll down a slope. Rocks derived from this type of material have repeatedly struck the San Miguel County Museum and other buildings on the north side of Telluride.

3.2.7.2: Accelerated colluvial slopes (csa)

Even though they may not be subject to mass failure, accelerated colluvial slopes are probably some of the most continuously active of the colluvial slopes. The soil experiences continuous creep* or episodic surface erosion from gullying and sheetwash* during summer thunderstorms and remains thin (i.e., less than about six feet in thickness) over all but the base area of the slope. Accelerated colluvial slopes are noted for their poor vegetal development due to a constant disturbance of the root zone. This occurs in certain areas on Wilson Mesa, where grazing has reduced the vegetal cover, exposing clay-rich, impermeable soils to raindrop impact. Due to the low potential for mass failure on (csa) slopes compared with (cst) areas, the former generally present a much lesser hazard to development. Headward erosion of gullies could pose a threat to structures by undermining on the downslope side. Also, rapid surficial soil movement in (csa) areas may lead to the accumulation of thick soil deposits on the upslope side of structures.

3.7.2.3: Moderate colluvial slopes (csm)

These slopes are characterized by a less intense operation of processes which act on (csa) slopes, and involve the creep and water transport of a soil mantle that is less than about six feet thick. The moderate level of colluvial activity on these slopes allows a more dense vegetal cover to develop than on (csa) slopes.

Most (csm) slopes in San Miguel County show little evidence of surficial erosion or mass movement. They are usually, but not always, less steep than (csa) slopes, and are found typically in the area of Coonskin Mountain, near to the Telluride Ski Area.

3.7.2.4: 'Inactive' colluvial slopes (csi)

These are areas where colluvial soils are thin (i.e., less than six feet thick) and slopes are less than 15 percent (8.5^{o}). It should be stressed that the term 'inactive' colluvial is relative to other colluvial sub-categories, in that a certain level of soil movement will always be present. However, these slopes show no obvious signs of surficial movement or mass movement of soil. The western edge of Wilson Mesa, west of Big Bear Creek, is classified as (csi) since it is underlain by generally non-expansive soils, and exhibits only slight colluvial activity. Many other areas within the plateau province, that are less than 15 percent slope, are underlain by Mancos Shale or the Morrison Formation; therefore, they are classed as expansive soil (es).

3.2.8: Physiographic floodplain (pf)

The physiographic floodplain is the portion of a river valley which undergoes frequent erosion and deposition changes, and where the threat of flood inundation supercedes all other hazards. The area mapped may not include all of the 100-year floodplain*, since interpretation in this study has not been based on stream discharge* records.

The principal area of physiographic floodplain recognized in the study area is the stretch of the San Miguel River valley, between Telluride and Society Turn. Although the extent of the physiographic floodplain can be inferred to a first approximation from the general absence of vegetation near to the stream channel, recent stream deposits are sometimes found in vegetated areas where tree species are able to tolerate periodic inundation. Presence of vegetation, including mature riparian stands of trees, therefore is no insurance against future inundation. There is no substitute for a detailed hydraulic analysis of a floodplain area to determine the 100-year floodplain limits; this is usually expensive to carry out, since detailed topographic surveys are necessary.

3.2.9: Swamp (sw)

A swamp is an area of seasonally- to perpetually-saturated ground, caused by a high water-table. In high alpine basins, swamps have developed in depressions created by ice erosion and deposition during the glaciations. Elsewhere, they occur in flat valley bottom areas that are poorly drained, for example, Swamp Canyon, about two miles southeast of the Old Ophir townsite. Usually, swamps can be clearly differentiated by the presence of standing water and marsh-type vegetation; for this reason, they should be easily recognized and avoided.

3.2.10: Subsidence (sb)

Ground subsidence involves the downward failure of a rock or earth material either under its own weight, or due to external loads, such as imposed by a structure. It is not an important feature on any of the geologic formations in eastern San Miguel County, although areas of extensive mine workings involving horizontal shafts should be investigated for incipient or potential failure areas if structures are proposed.

3.2.11: Tailings (tail.)

Tailings consist of fine-grained felspar* and quartz detritus from a rock milling operation. The most limiting hazard relates to the sudden, unexpected failure of the tailings deposit, due to stability miscalculations or negligence. Small inactive deposits on steep slopes should also be viewed with caution, in addition to the large ponds, since mine shafts are lines of accelerated ground-water drainage. Under high flow rates, accelerated erosion of tailings may take place and through drainage may create high seepage forces and promote local mass failure of the deposit. The incidents at the Standard Metals pond at Silverton in 1975 indicate that large-scale failure of an active tailings pond can occur, despite regular maintenance.

3.3: Mitigation of geologic hazards

Because the purpose of this study is to present a preliminary identification and interpretation of areas subject to certain types of geologic hazards within the County, it is not within the present scope to discuss hazard mitigation in any detail. Instead, certain broad categories of hazard are considered and broad suggestions are made. Following the discussion of mitigation of snow avalanche hazards in Section 4.6, an overall assessment of some of the aspects of mitigation is given in Section 5, under the heading of general recommendations.

The hazards listed in legend (1), Appendix 1, can be broken down into three broad categories:

(1) Those involving a high level of geologic activity on slopes, including slope failure and rockfall. The categories included are: rockfall, rock glaciers, active, or potentially-active landslide areas, talus slopes and talus slide areas.

(2) Those involving a threat of inundation, either from stream floods or debris flows. The categories included are debris flows, physiographic floodplains, and debris fans, irrespective of whether they bear recent evidence of debris flow deposition. Swamps are a somewhat less hazardous component of this category.

(3) Areas involving significantly lesser slope instability hazards than those listed in (1) above, comprising colluvial slopes, areas of expansive soil, subsidence and tailings.

The three-fold classification above is the basis for a brief treatment of hazard mitigation. The categories included in (1) above usually involve a localized failure of soil or talus material, either in the dry state or in the presence of variable amounts of ground water. In view of the high level of geologic instability on a year-round basis in many high basins beset by these types of hazards, avoidance would be the best means of 'mitigation'. As will be seen in Sections 4 and 5, many of these areas are also snow avalanche zones, so that consideration of geologic hazards alone may not be sufficient. Certain areas within the county have a lesser rate of rockfall and talus development than others, for example, but these have not been identified by sub-categories. It is possible that deflecting structures or structural re-inforcement of upslope walls would constitute sufficient defense against rockfall in less active areas, for example, below the cliffs formed by the Cutler, Dolores, Entrada and Wanakah formations along the San Miguel Valley. Within the Tertiary volcanic and intrusive area, however, the rate of rockfall is such as to make any type of mitigation procedure non-feasible from a benefit-cost standpoint, for most types of structure. However, mining operations have to be evaluated on a different scale from private dwellings.

Whereas the hazards in (1) tend to affect large, contiguous areas, particularly above timberline, areas subject to flood and debris flow hazards in (2) tend to be much more linear in plan form, for example, recent debris flow levées traversing an otherwise stable debris fan. As noted for category (1) areas above, avoidance is the best means of defense in the case of active debris flow tracks and all areas designated as physiographic floodplain. Apart from the fact that many debris fans within the mountain province are also snow avalanche runout areas, certain fans would be classed as less active than others in terms of frequency of debris flow events. It is possible that debris flow or flood hazards could be mitigated on some of the fans that are not also avalanche runouts, for example, those that are constructed along the San Miguel Valley, west of Society Turn. In these areas, a study of the stability of the catchments would be advisable, before any specific engineering designs are considered. Since debris flows are known to take courses across debris fans that depart markedly from 'expected' trajectories (i.e., the line of maximum gradient), it might be good policy to install a deflecting structure at the apex of the debris fan, to lessen the amount of uncertainty as to the future course of deposition on the surface of the fan. An artificially enlarged stream channel at one side of the fan could then be used in conjunction with the deflecting structure, to ensure that most debris would not reach the surface of the fan. However, repeated deposition in the channel would necessitate clearing from time to time, otherwise the channel area would aggrade to the same general level as the fan, and it would no longer serve its intended function as a safe conduit for debris.

The categories outlined in (3) above for the most part cover the broad term 'potentially-unstable' slopes. This is particularly true of (cst) areas, where the thickness of the overburden (whether of glacial or colluvial origin, or both) is generally greater than six feet. This means that these slopes are subject to periodic mass failure. Particular care should be exercised in the excavation of soils in (cst) areas developed on sedimentary formations that contain cohesive, shale units (e.g., the Cutler, Morrison and Mancos formations. Although most roadcuts may be stable when the soil is drained, failure may occur when the soil is wetted, either from natural percolation of ground water, or from irrigation or septic tank operation. For this reason, all stability analyses for cuts in (cst) material, particularly where it overlies shale formations, should take account of the most limiting, water-saturated condition.

Provided that snow avalanche hazards do not also exist, the mitigation of purely geologic problems within the remaining categories in (3) above can probably be accomplished at reasonable cost, using well-established engineering techniques. The appropriate action can only be decided upon after a detailed site investigation, including standard soils tests. A more detailed treatment of these methods is, therefore, beyond the scope of this study.

SECTION FOUR

SNOW AVALANCHE HAZARDS

4.1: Introduction

The purpose of this section is to provide background information on snow avalanche phenomena that is adjunct to the delineation of avalanche areas within the County according to the legend in Appendix 2. In contrast to the large number of geologic investigations in the study area, there is an almost complete lack of published sources on snow avalanching in eastern San Miguel County. In this regard, the study reported here is the first systematic attempt to map avalanches and potential avalanche areas on a county-wide basis. Previous work has been focused in the valley of Howard Fork, between Old Ophir and Ophir Loop (Ives at al., 1976). This study provides a detailed treatment of the avalanche problem relating to Spring Gulch and evaluates the return period of large avalanches. Large avalanches which cross the county road between Old Ophir and Ophir Loop are also mapped and discussed.

Since the fall of 1971, the INSTAAR San Juan Avalanche Project, based in Silverton, has provided regular observations along Highway 550 in San Juan and Ouray counties, noting avalanche occurrences, and has supplied a continuous record of meteorological observations to support the avalanche work, derived from a network of stations based on Red Mountain Pass. The purpose of the study has been to evaluate conventional and statistical methods of avalanche forecasting and develop a framework for short-term prediction of avalanches, on an operational basis. The project has examined the causes of dry and wet snow avalanches in the San Juan Mountains, and the conclusions of the study should be applicable to avalanche problems in San Miguel County (Ives et al., 1972, 1973; Armstrong et al., 1974, 1976). Although the project has provided some clues as to the relative frequency of avalanche activity on certain paths outside of the San Miguel County area, many paths monitored have not been observed to avalanche to their probable maximum extent over the five year period. Therefore, other data sources, discussed below, have been consulted to define the probable long-term extent of avalanching within the County area, commensurate with land-use requirements.

A study by Frutiger (1970) pointed out the limitations of relying on a single data source in mapping avalanche areas, and suggested that a combination of of topographic and vegetation factors be used, supplemented where possible, by eyewitness accounts from local residents and any chronicled information, such as newspaper reports. Previous INSTAAR experience in San Juan County suggests that close agreement can be obtained sometimes between known historical occurrences (See B. Armstrong, 1976) and the boundaries obtained by photo-interpretation and field checking. The study of Ives et al. (1976) indicates some of the problems of reconciling historical and tree-ring evidence for occurrences emanating from Spring Gulch.

4.2: Snow avalanche terrain

Snow avalanches occur naturally from the acceleration of a failed mass of snow that has become fluidized to some degree by air entrainment. Often, avalanches are confined to distinct paths, in which three components are recognized: starting zone; track; and runout (Figure 3). In this study, only avalanche path outlines are depicted, for reasons of cartographic simplicity, together with potential avalanche areas (Appendix 2). However, since any discussion of avalanche frequency and hazard mitigation must take account of the components of avalanche terrain, a brief treatment of each component is given below.

(1) Starting zone. This is the zone of origin for either loose or slab avalanches. Nearly all vegetation damage is due to the latter type, since slab avalanches produce the larger volume of fluidized snow. As Salm(1975) points out, size of starting zone is related to size of avalanche and velocity of flow: large starting zones produce the largest avalanches, and due to the great depth of flow of these events, attain the highest velocities (See Track, below). This principle was used by Bovis and Mears(1976) in a prediction of the runout distance of large avalanches based on starting zone area.

Many avalanche starting zones extend above timberline in San Miguel County, for example, Spring Gulch and many other named paths along Howard Fork valley, and most of the paths along Bear Creek. However, not all areas above timberline are avalanche starting zones, due mainly to a combination of slope (too steep), snowpack thickness (too thin) and terrain roughness (too rough). The scale of this study has permitted only the slope-angle factor to be evaluated, based on topographic map measurements. It is generally accepted that most avalanches start on slopes of between 30 and 45 degrees (60 to 100 percent) (Mellor, 1968; Martinelli, 1975). In this study, all slopes steeper than 30 degrees above timberline, are considered to be active avalanche areas and are depicted by fine stipple on the maps (Appendix 2). Slopes steeper than 45 degrees are also included in the mapped starting zones, since they are probably areas of frequent loose-snow avalanching.

(2) Track. In the case of a confined avalanche path (Figure 3a), the point of transition between the starting zone and the track occurs where flowing snow becomes confined laterally. For most open slope, or unconfined avalanches (Figure 3b), this distinction cannot be made, since at no point is flowing snow truly confined; the width of the 'track' in the latter case, then, is closely related to the width of the failed slab in the starting zone. Since most of the avalanche paths in eastern San Miguel County are confined to some degree, the comments in this section apply mainly to confined avalanches.

The track serves as a conduit for flowing snow and is the zone in which depth of flow and velocity of flow are maximum. This means that the track of an avalanche path is often clearly demarcated on a slope by the conspicuous absence of timber, bounded by distinct trimlines (Plates 13 and 16). In the absence of vegetal evidence, the path followed by avalanching snow can be evaluated from topography, along lines that are contiguous with known, or probable, starting zones.

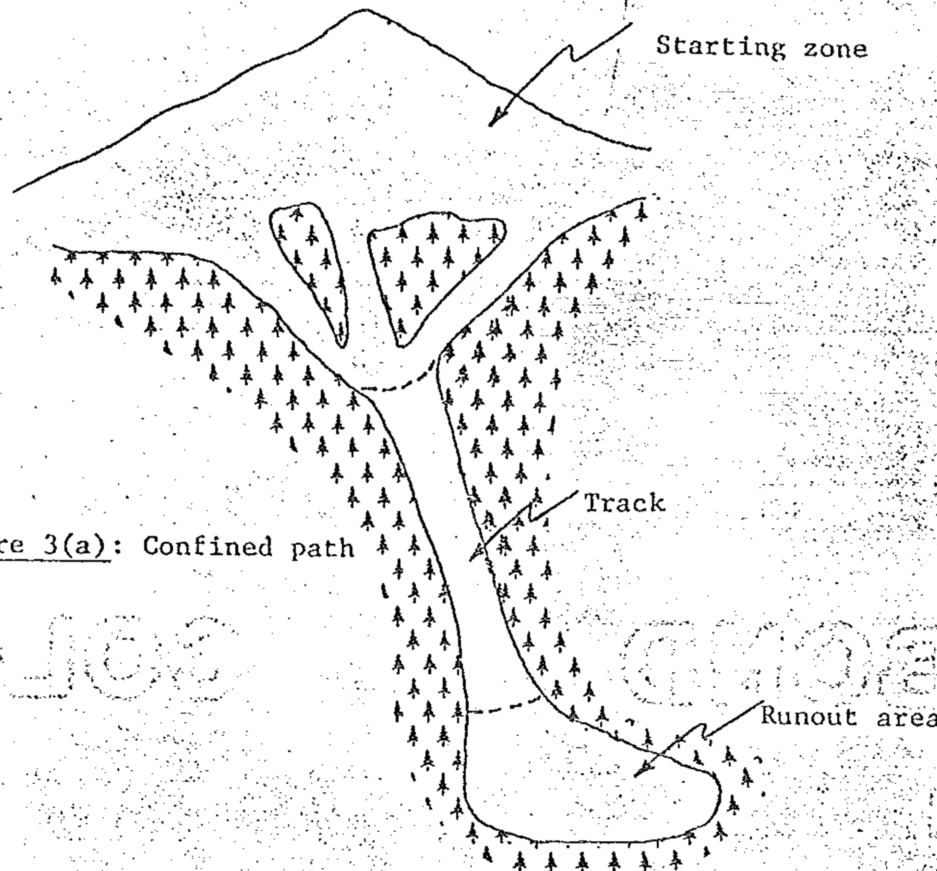

Figure 3(a): Confined path

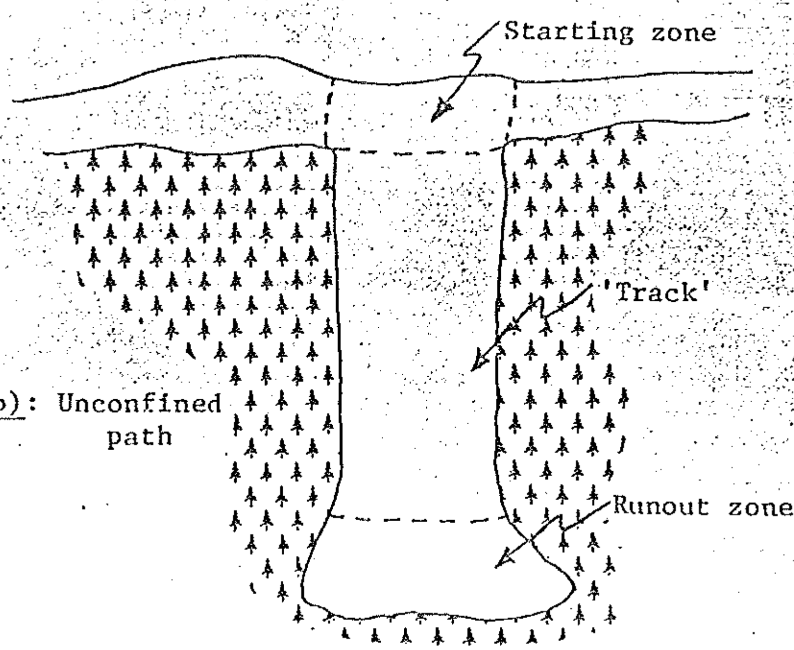

Figure 3(b): Unconfined path

Certain avalanche tracks are too narrow to be depicted accurately at the map scale of 1 inch to 2,000 feet, and are shown by arrows (Appendix 2). Although involving a lesser volume of snow than the large paths, small tracks generate the same kinds of hazards and, for this reason, should not be dismissed as areas of lower hazard. (The arrow symbols are retained on the third, combined hazard map series discussed in Section 5).

In view of the acceleration of avalanching snow to velocities of over 100 mph along the avalanche track, (See Types of Avalanches, Section 4.3) it hardly seems necessary to emphasize the potential threat to fixed structures in their path. The level of hazard may be unacceptably high also to skiers and other winter recreationalists, who simply pass through the track area. Since many tracks approach 30 degrees in longitudinal slope; avalanches can also start in the steeper portions of the track, as well as within the starting zone as defined above, under conditions of artificial, impulsive loading.

(3) Runout zone. Of the three zones defined in Figure 3(a), the runout zone is the most important from the standpoint of land-use zoning, in that other factors such as slope stability and drainage may not impose notable constraints on the design or location of structures. Therefore, runout areas which appear 'safe' during the summer may be subject to unacceptable hazards during the winter season.

The transition between the track and runout zone occurs where snow is no longer laterally confined, so that appreciable spreading of the flowing mass occurs. This, combined with the lesser longitudinal slope of the runout area compared with the track, causes the avalanche to decelerate and dissipate its flow energy over a broad front. In some cases, large avalanches possess sufficient energy to flow up the opposing (adverse) valley slope for a considerable vertical distance; in these instances, the runout zone straddles the lower part of the valley. Notable examples are Spring Gulch, at Ophir, and the larger paths along Howard Fork (Magnolia, Badger and St. Louis),and many paths along Bear Creek. Damage to standing timber in this type of situation, often for a considerable distance above the valley axis, is a striking testimony to the kinetic energy of highly fluidized snow.

Although not depicted by a separate symbol on the avalanche hazard maps, the runout zone has received the greatest attention during the photointerpretation and field checking phases of the study. Starting zones and tracks are often clearly identifiable, particularly on timbered slopes; conversely, the determination of the probable maximum runout distance of avalanches in a given area is usually more difficult to achieve, and ideally, should be based on several methods, some of which are discussed below.

As a large avalanche decelerates and comes to a halt, deposition of entrained debris takes place, leaving behind a vestige of avalanche motion in the form of flow-aligned timber (Plate 18). This type of evidence fixes the general location of a runout area, but usually does not fix the boundaries of a maximum potential runout area for a track, since it is likely that the airborne component of a large avalanche will travel beyond the debris limits. (See Types of Avalanches, Section 4.3). A more accurate estimate of the maximum probable runout area is provided by damage to mature timber stands: lines of evidence include broken trees due to causes other than windfall, and trimming of branches from trees exposed to powder avalanche or ground avalanche impact (Plate 17).

The limits of the runout area can also be fixed mathematically for avalanches of specified dimensions, using runout equations derived by Voellmy (1964), although predictions based on these equations are accurate only when the relevant flow parameters are accurately measured or estimated, and this has proved difficult to do without observations of avalanches in motion (Schaerer, 1974).

Ideally, there should be convergence between the results obtained from the two independent methods of estimating runout distance, namely, the mathematical and the empirical approaches. Acceptable convergence was obtained by Ives et al. (1976) in a study of the Spring Gulch slidepath at Ophir in San Miguel County. Generally, field evidence is to be preferred over calculations based on theory, particularly when the coefficients in the runout equations are subject to variation according to the type of snow involved in the avalanche, and the roughness of the terrain over which the avalanche runs. When field evidence is totally lacking, as on bare slopes, the possible pitfalls of using unverified, theoretical estimates of runout distance should be fully recognized.

A statistical approach to estimating runout distances for large avalanches has been proposed by Bovis and Mears (1976), based on starting zone area alone. This method probably has no more than about sixty percent efficiency, and at the time of writing, is untested, and will require refinement before producing predictions accurate enough for land-use applications.

4.3: Types of avalanches

Some of the preceding discussion has implied that the type of avalanche is related to the attainment of the maximum runout limit on a given path. A basic division is recognized between dry and wet snow avalanches and this represents a considerable contrast in material properties, and hence in flow regime.

A massive failure in unconsolidated dry snow may lead to an avalanche of considerable depth. This is the so-called 'powder' avalanche, which can exceed 200 feet in depth and attain speeds of well over 100 miles per hour. Although the density of the airborne avalanche is only a few times greater than that of air, the high flow velocity of the mass accounts for its destructive potential. Also, this type of avalanche tends to flow over topographic barriers rather than being deflected or dammed; therefore, a considerable area may experience impact pressures which exceed structural design limits. Although substantiated by few actual observations of avalanches in motion in the study area, it is likely that the maximum runout limits on most paths are defined by this type of avalanche.

It is only rarely that a dry snow avalanche will become totally airborne: usually, most of the mass is concentrated as a much more dense, dry flowing avalanche, above which a variable amount of airborne snow may develop, depending on snow and terrain conditions. Dry flowing avalanches can attain speeds near to 100 miles per hour, yet are susceptible to deflection by topographic obstacles. Due to the lesser velocity of flow and lesser degree of spreading of this type of avalanche compared with airborne avalanches, the runout area of a dry flowing avalanche will almost certainly be smaller than a large powder avalanche on the same path. This is borne out in the Ophir study of Ives et al. (1976).

Wet flowing avalanches have a density up to about half that of water, compared with dry flowing and powder avalanches, which have densities of about one tenth and one hundredth that of water, respectively. Because of the higher snow density, the speed of wet flowing avalanches rarely exceeds 70 miles per hour, with typical values around 30 to 40 miles per hour. Nevertheless, wet avalanche impact pressures may be higher than those produced by either dry flowing or powder avalanches although this is offset by the much smaller areas affected by wet avalanches on most slide paths.

Wet flowing avalanches are very sensitive to terrain irregularities, and like debris flows may produce a deposit consisting of several 'fingers', such as occurred in the large wet avalanche at Ophir in spring 1973. Because wet avalanches occur in spring, they often traverse bare ground in the runout area, causing considerable retardation of the flow and piling-up of snow in the runout zone, a tendency enhanced by the cohesiveness of wet snow. Deposits thicker than 30 feet can occur in this way and have produced static loads sufficient to cause structural failure and even capsizing of railroad locomotives (Voellmy, 1964).

Clearly all types of avalanches are potentially very destructive, irrespective of flow density and velocity. In the case of powder avalanches, aerodynamic factors need to be taken into account, including lift forces on structures (Sommerhalder, 1967). Dry flowing and wet flowing avalanches are not free to flow around an obstacle like a powder avalanche, and instead, dam up and behave as compressible solids (Mellor, 1968). Apart from the type of loading associated with the impact of each type of avalanche, the different proportion of the runout area affected by single events of each type is perhaps the most important distinguishing factor from a land-use zoning point of view. This should be evaluated for each path from detailed studies (e.g., Ives et al., 1976).

4.4: Avalanche magnitude and recurrence interval

From the standpoint of the land-use planner, estimates of the frequency with which the maximum runout limits are attained by avalanches on a given path are obviously of crucial importance. If it can be demonstrated, for example, that large avalanches engulf the entire runout area with a mean recurrence interval of twenty years, then it is likely that structures with an expected lifespan of, say, forty years, will be damaged or perhaps destroyed within this period. The Ophir townsite study of Ives et al. (1976) pointed to a return period of about twenty years for large avalanches emanating from Spring Gulch, based on vegetation (tree-ring) analysis at the fringes of the runout zone. In this type of situation, development on the runout fan would be ill-advised, unless defense structures were erected or buildings suitably reinforced to withstand the expected impact pressure from avalanches (See Mitigation, Section 4.6). If the cost of such structures could not be justified, then development of the site would be declared economically non-feasible, factors of human safety aside.

One point emerging from the Ophir study and earlier INSTAAR work on snow avalanche recurrence interval at Vail (Krebs (ed.), 1973), is that the problem of recurrence can only be approached satisfactorily by a detailed site investigation of the vegetal evidence. Under favorable conditions, tree-ring analysis can provide about a hundred-year record of events, and enable the mean return period of large avalanches to be estimated. The only other reliable method is historical documentation, though due to the sparse population over much of the San Juan region, there is a general lack of information for most slidepaths. The Swiss are more fortunate in this regard due to long cadastral records, but despite this log of information, avalanche disasters have occurred within this century, that could probably have been avoided had the historical record been consulted in detail.

No division of the runout zone into zones of greater or lesser hazard has been attempted here and, in view of the number of avalanche paths mapped, a considerable amount of fieldwork and laboratory analysis would be necessary to make even rough estimates of the mean recurrence interval for events of a specific magnitude on particular slidepaths. This will remain a matter for detailed investigation as and when the need arises in San Miguel County. Again, the objective here is to delineate paths and map the approximate limits of the probable maximum runout area.

Once an estimate has been obtained for the recurrence interval of avalanches of a specific magnitude, it is possible to make an estimate of the distribution of impact pressures within the runout zone corresponding to this magnitude of an event. It is relatively straightforward to solve for impact pressure at a given point in the runout, once estimates of flow velocity and density have been made, and the manner in which flow velocity decays across the runout has been specified mathematically (e.g., Sommerhalder, 1967). However, in the absence of an accurate recurrence interval estimate, division of a runout area into zones of variable impact pressure is not meaningful, even if based on some assumed maximum event for a particular slidepath.

At present, two ends of the spectrum of avalanche recurrence are established for large events within the San Juan region. On the one hand, certain paths are known to avalanche to the maximum of their respective runout limits every year; this may occur in many areas above timberline, and on some paths along Bear Creek and Waterfall Creek. Elsewhere, for example, the Spring Gulch avalanche at Ophir, the recurrence interval of events which sweep over the entire runout area is estimated to be on the order of twenty years. Presumably, there are many paths on which the largest event has a recurrence interval between these limits.

It can be argued that the recurrence interval for the Spring Gulch path may be longer than many in the San Juan area, in that it faces south. Southerly exposure, especially on steep slopes, means high solar energy receipts and, consequently, an accelerated rate of new snow settlement, which, in turn, can lead to a strengthening of the snow pack. Also, it is likely that the rate of 'depth hoar' formation is lowest on south-facing slopes, since the mean temperature difference between the base and the top of the snowpack is smaller than on north-facing slopes where radiation receipts are much lower in winter. One of the important facts verified by the INSTAAR San Juan Avalanche Project is the importance of weak depth hoar layers in snow slab failure and detachment on avalanche slopes (Armstrong et al., 1974, 1976).

The preceding discussion is not meant to imply that depth hoar cannot form on south-facing slopes; rather, it suggests that the potential for the development of large avalanches should be reduced on south-facing slopes. This lower potential should, in turn, be reflected in a longer return period for large avalanches on south-facing slopes. If this is the case, then the Spring Gulch return period of twenty years may be longer than for events of corresponding magnitude on many other large avalanche paths in the San Juan region. From this it can be tentatively concluded that a significantly large proportion of avalanche paths in the county area may have a return period for events which encompass the entire runout area that is less than the lifespan of most structures, assumed here to be about forty years. A good working principle in land-use decision-making is to discourage any further construction within known avalanche runout areas, and to prohibit such construction in instances where detailed site studies reveal a return period for large avalanches that is unacceptably short in terms of the anticipated life of the structure.

Finally, some comment is in order as to the meaning of terms such as the 'twenty-year avalanche'. Let us suppose that a return period of twenty years is established for large avalanches which engulf the entire runout area on a particular path. This means that, on the average, the probability of occurrence in any one year is five percent. If the reasonable assumption is made that such an extreme event cannot occur twice in one avalanche season, for reasons of snowpack regeneration in the starting zone, then occurrences from year to year can be treated as statistically independent events. This means that the conditional probability of an extreme event occurring in a particular year, given that such an event has occurred in the preceding year, is the same as if the event in the preceding year had not occurred. In other words, the mean recurrence interval of twenty years does not exclude the possibility of an extreme event occurring in consecutive years. This contingency is easily overlooked in a discussion of recurrence intervals.

4.5: Potential avalanche areas

These areas are represented by a coarse stipple on the avalanche hazard maps and, as such, are readily distinguished from active avalanche paths. All timbered slopes steeper than 60 percent (31°) and above about 7,000 feet elevation are included in the potential category. Avalanches do not appear to be occurring on these slopes at present, principally because of the arresting influence of trees on the snowpack. Although trees may provide poor protection from moving snow, they may serve a function similar to man-made supporting structures by relieving downslope shear stresses. It is likely that a back-pressure zone (McClung, 1973) develops upslope of each tree, with width proportional to the projected area of its trunk along the local fall-line. Densification of snow within the back-pressure zone means that the rate of shear strain at a given level in the snowpack, will decrease as a function of time. By contrast, absence of trees in avalanche starting zones can lead to an accelerating rate of shear strain from creep deformation, and this has been cited as a possible cause of avalanche initiation (Mellor, 1968). Other modes of failure have been proposed, and these are discussed in Brown et al. (1972).

It is clear that removal of large swaths of timber from potential avalanche slopes is unwise. In fact there are well-documented cases where this has led to the development of new avalanche areas where formerly few, or none existed (LaChapelle, 1966). The Austrian example discussed by LaChapelle points to the enormous cost of reforestation in mountain areas; the cost of completing the program in the Tirol region alone was estimated at $20 million, about one percent of the entire annual national budget! Also, rates of regeneration of native species close to timberline in Colorado are not known in any detail; therefore, estimates of the probable cost of reforestation per acre would be difficult to make, other than assuming that the cost would greatly exceed the market value of the timber removed. A further consideration is that flat, developable land located downslope from a potential avalanche area may be rendered decidedly unsafe by man-induced avalanches produced by a logging operation or fire. In the most extreme case, a rezoning of the developed land as open space might be necessary, with all its attendant legal problems of compensation.

Two qualifications should be made concerning the identification of potential avalanche areas. First, avalanches can start on slopes of less than 31°, although this is relatively uncommon and, almost certainly, restricted to untimbered slopes. Also, gliding of the entire snowpack across the ground surface can occur on slopes as low as 10° to 15° (Mellor, 1968), particularly when the snowpack is water-saturated and in a slush-like condition. Fortunately, due to climatic and snow conditions, snow gliding does not appear to be a problem in the San Juan Mountains. A second consideration is that some potential avalanche areas may in fact experience periodic avalanching. If this occurs as a slow-moving ground avalanche, confined to the zone beneath the forest foliage, it may leave only subtle evidence of its motion in the form of slight impact damage to bark on the upslope side of trees. The Blackburn slide, north of Silverton, runs to Highway 550, apparently about once in four or five years. Were it not for the readily-identifiable snow deposit by the roadside, this active path would escape detection.

The evaluation of these situations on a county-wide basis is beset by the same problem that faces the estimation of recurrence interval on known avalanche paths, namely, a general lack of direct observation of avalanche occurrences, with the exception of those intersecting major highways.

4.6: Mitigation of snow avalanche hazards

There are three principal ways of protecting structures from the destructive impact of avalanching snow that are treated with varying emphasis in Frutiger (1962), Mellor (1968) and USDA Forest Service (1975).

The first possibility involves the erection of snowpack supporting structures in avalanche starting zones to prevent avalanche initiation, or at worst, to limit releases to small sluffs. The engineering technology of these installations is fairly well-established, and various designs are proposed in the references cited above. Cost estimates for this type of work are based mainly on Swiss work, since for a variety of reasons, American involvement has been slight so far. Labor costs are likely to be high in this country, since unlike Switzerland, the use of cheap, imported labor is discouraged for social reasons. Costs per acre are, therefore, estimated to be $250,000 or possibly higher, depending on the ruggedness of the terrain, the number and types of structures required, and proximity of the site to a major highway. Unless the protection of an entire town is at stake, as is the case in many Swiss areas, the low benefit-cost ratio in most Colorado mountain situations means that starting zone structures are not financially feasible.

The second possibility concerns the construction of avalanche deflecting or arresting structures in the runout zone. Since this cannot be divorced from the structural re-inforcement of buildings, these two aspects are considered jointly here. Deflecting and arresting structures must contend with large avalanches, travelling at high velocities, therefore, most designs involve a considerable amount of earth moving to produce the required configuration of deflecting walls, dams and ditches. Clearly, this involves an appreciable disfiguration of a landscape, and may in fact defeat the entire purpose of a proposed development in that the scenic quality of the site is marred irreparably. Disguising structures with forest plantations may actually lead to an increased hazard level, since trees snapped off by a large avalanche will very likely be used as battering rams within the runout zone (Frutiger, 1970). Many designs have been proposed for the structural re-inforcement of buildings, and for cost reasons, most of these involve wedge-shaped appendages to split the flow of a ground avalanche, since this is cheaper than building a wall that will withstand frontal impact and subsequent damming pressures. Although this type of structural modification may enable a building to withstand avalanche impact, the danger exists of diverting flow onto adjacent buildings, which may not be structurally re-inforced, or shifting the avalanche into areas which were considered safe before the structural changes took place. For this reason, building re-inforcement must be part of a wider program of avalanche deflection or containment using earthworks, otherwise catastrophe may visit undefended areas formerly considered to lie outside of the runout zone. As with starting zone modification, the amount of engineering work needed to adequately protect a runout area seems unwarranted, unless the defense of a pre-existing settlement is at stake. Following the avalanche disasters in Switzerland in the early 1950's, certain alpine settlements were protected by starting zone and runout zone defences, at enormous cost, and with immeasurable loss in scenic quality.

The third method requires the periodic control of avalanches in the starting zone, using explosives or other energy sources to produce a timely release of the snowpack as a series of small avalanches, most of which will not (hopefully) reach the runout zone. There are several complications in this scheme, not the least of which is controlling the size of the avalanche produced by external stimulus; an unexpectedly large release could engulf the buildings below. Avalanche control by artillery along highways does not face this problem, since traffic can usually be kept well beyond the runout area until all reasonable danger is past. The second problem relates to the evacuation of a community if the danger of a large artificial release is considered high. This would require a well-executed operation and could involve legal complications, particularly when citizens are inconvenienced in a situation which turned out to be a false alarm. This unfortunate circumstance might exert a critical influence on future evacuation decisions and, thereby, expose the community to an unreasonable level of hazard.

From the above, it is seen that the prospects for avalanche control are not good; Swiss authorities have been forced to make decisions in this area for the sake of existing communities, a situation which can largely be avoided in Colorado, given a timely recognition of actual and potential avalanche areas.

SECTION FIVE

COMBINED HAZARD REPRESENTATION AND GENERAL RECOMMENDATIONS

5.1: Introduction

An estimate of the overall degree of hazard from both geologic and snow avalanche phenomena, is desirable for regional land-use planning. The five-fold ordinal (rank) scale discussed here forms the basis for the Overall Hazard series of maps which are designed to meet that need. As noted in Section 1.1, these maps are adjunct to the separate geologic and avalanche series.

It should be noted that rank of a hazard category is a qualitative, rather than a quantitative, measure of the hazard. For example, an area mapped as Category II is not necessarily half as hazardous as an area in Category I, as far as frequency and magnitude of events. Also, the difference between adjacent categories is not constant; for example, the difference between Categories I and II is high, and involves an abrupt change from active avalanche to potential avalanche, notwithstanding appreciable contrast in the level of geologic instability. The transition from Category IV to Category V, however, involves a much smaller difference in the level of geologic activity.

The assignment of areas to ordinal categories is made according to the most limiting hazard (Section 3.1). For example, many avalanche tracks in Category I exhibit only a moderate level of geologic instability (i.e., soil and rock instability), so that the high hazard rating derives from avalanches. Conversely, recently active landslide features in the plateau country underlain by Mancos Shale are mainly free from snow avalanche hazard, for reasons of elevation and slope; therefore, a Category I rating for these areas is a reflection of active or potential slope failure.

These two illustrative examples demonstrate that the Overall Hazard maps can only be completely understood when studied in combination with the separate geologic and avalanche hazard series of maps, particularly when the mitigation of hazards is under consideration. The first example, involving avalanche hazard, would involve mitigation of the effects of high impulsive and static loads to the superstructure of buildings located in an avalanche runout area. The second example would require a suitable combination of foundation design and slope modification to alleviate a mass failure hazard, a fundamentally different engineering situation from the avalanche problem.

From the standpoint of land-use zoning, the Overall Hazard maps are a basic set of documents in that all hazards are considered. A possible framework for subsequent decisions is illustrated in Figure 4, which emphasizes vertical integration of the map series and the scale limitations of this study.

An important consideration in assigning areas to one of the five categories

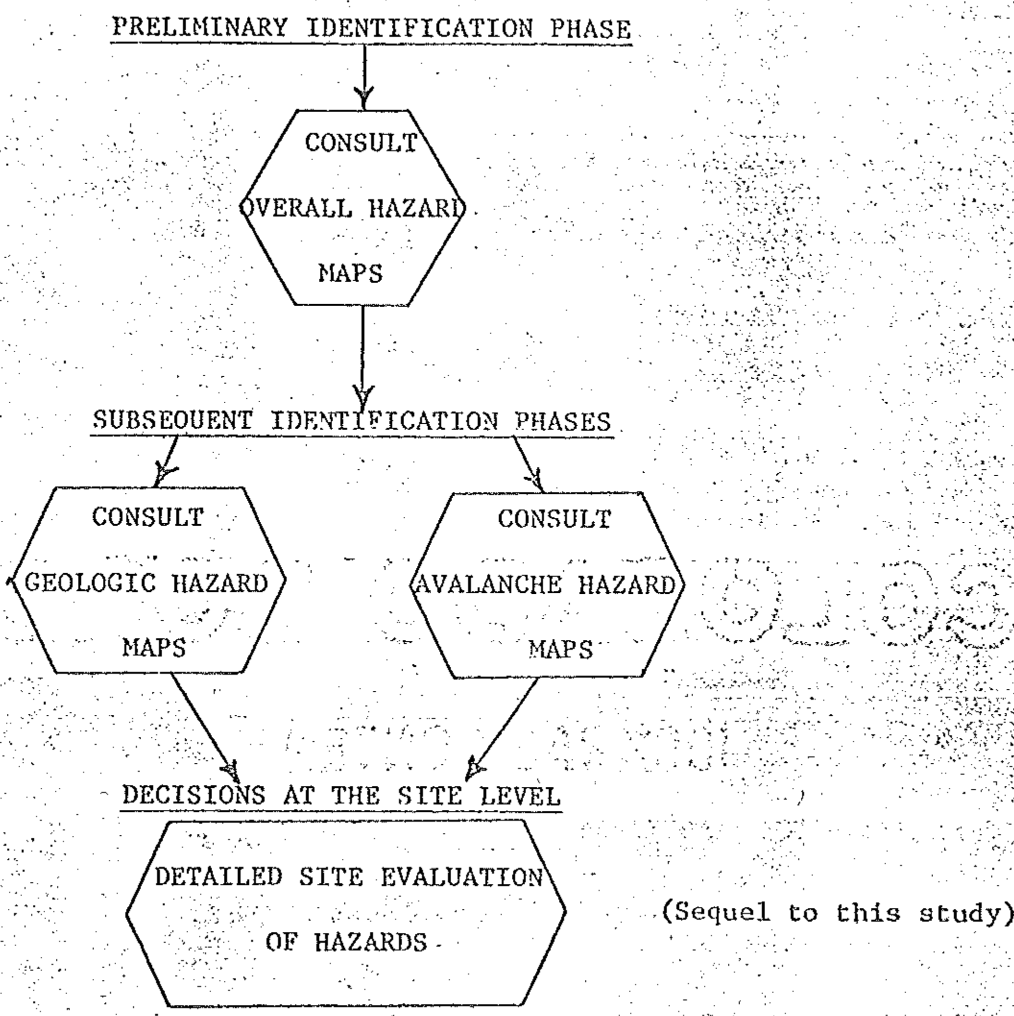

Figure 4: Use of the hazard maps in land-use decision-making.

is that the status of an area may not remain constant if an appreciable level of terrain modification takes place, such as when a potentially unstable slope undergoes mass failure due to excavation, water absorption from septic systems or irrigation, or a combination of both causes. Such an event would necessitate the re-classification of the affected area and may necessitate a re-evaluation of the safety of inhabited areas downslope. This problem was discussed in the section on Potential Avalanche Areas (Section 4.5) yet applies to purely geologic events also. For example, a slump may subsequently become mobilized as an earthflow or a debris flow. Also, categories which involve potentially-unstable slopes may change their status in response to natural events, such as forest fires, and severe storms or floods. The county authorities should note any such changes, and ensure that the hazard maps are up-dated for future users.

Comments on land-use constraints in this section are confined mainly to fixed structures, such as dwellings and roads, that have expected lifespans of decades rather than years; therefore, it is important to consider encounter with hazardous events the magnitude of which might be near to the maximum potential level of activity for a particular category. However, the expected life of a structure should not be used as a hard-and-fast criterion in areas of high hazard. Depending on the recurrence interval of highly destructive events, a temporary occupance of an area may involve as high a risk as a longer-term development, since the statistics of extreme events can only be used to assign an average probability for the occurrence of an event <u>within any given year</u>. Unless all the physical factors that contribute to the occurrence of an extreme event are monitored through time, there is usually little basis for predicting time of occurrence of an extreme event.

5.2: General recommendations

Some of the possible methods of mitigating hazards have already been discussed (Sections 3.3 and 4.6). Since the combined hazard legend described above involves both geologic and snow avalanche effects, general recommendations on land-use must consider the possibilities for mitigating both types of hazard. Hazards should be evaluated on a site basis, when the configuration and purpose of a proposed development is known. For this reason, only the broad implications of combined hazards for certain types of land use can be mentioned in the sections which follow. The examples used are illustrative and by no means exhaust the possibilities.

5.3: Category I

This is the category having the highest overall hazard from geologic and snow avalanche phenomena. Two types of situation qualify for a Category I rating:

(1) All areas subject to rockfall, such as rockfall source areas (rf), talus slopes (ts), including talus slides (tss) in addition to active or recently active landslide activity (ls,) and active or recently active debris flow areas (df), whether overlapped by snow avalanche tracks or not. (Abbreviations refer to the geologic legend in Appendix 1.)

(2) All active avalanche areas, whether or not other geologic factors are present. Small avalanche paths, mapped as (⟶) in Appendix 2 are included.

Recommendation 1A (R1A)

In view of the preceding discussion in Sections 3.3 and 4.6, it is evident that the cost of mitigating hazards in most Category I areas would be extremely expensive, and probably would not be financially worthwhile when added construction and site engineering costs are weighed against expected benefits. Fixed structures erected in this zone run a high risk of sustaining appreciable damage to both superstructure and foundations. Instances of overlap between snow avalanche tracks and active geologic hazards involve unstable conditions on a year-round basis. These areas should be avoided at all cost when planning the location of any fixed installation.

Recommendation 1B (R2B)

The remainder of Category I, not included under R1A, involves overlap between snow avalanches and less hazardous geologic instability. However, the fact that part of the year may be largely free from hazards (i.e., avalanche free), may not constitute a reduced hazard overall, since the peak overpressures from avalanche impact will be approximately the same as in areas listed under R1A, and will be largely independent of geologic conditions. Since Category I areas included here under R1B involve mitigation of avalanche hazards alone, the guidelines in Section 4.6 should be consulted before plans relating to fixed structures, in particular, are formulated.

Although the fringes of many avalanche runout areas may involve reduced hazard, this can only be evaluated accurately from a detailed site investigation of avalanche frequency and magnitude. These data must be interpreted in terms of the expected life of the structure and its purpose. For reasons of cost and safety, it is likely that many of the remaining areas in Category I not included in R1A should be avoided if possible and considered as sites for development only when all other local alternatives have been exhausted.

Recommendation 1C (R1C)

The content of R1A and R1B relates to fixed structures. However, all Category I areas involve some degree of avalanche hazard during the winter season. It is recognized that the level of hazard is highest in the starting zone and track segments of an avalanche path and generally diminishes toward the fringe of the runout area. Nevertheless, all persons entering Category I areas in winter should be aware of the potential avalanche danger and should consult regional hazard warnings. This applies particularly to winter recreationalists who may desire to enter areas for which little information on avalanche frequency exists.

It should be stressed that the avalanche hazard maps are not intended to be used as a hard-and-fast guide to avalanche hazard by skiers, snowshoers and the like. Many small areas where over-snow travellers could initiate an avalanche release have not been depicted because of the scale of the maps. Therefore, certain areas designated as avalanche-free may contain small pockets of instability which, although posing no appreciable threat to buildings or communications, are sufficient to cause injury or death from snow avalanching.

Experience has shown that the small avalanche release takes the greatest toll of life (Williams, 1975).

5.4: Category II

This category comprises debris fan areas that are neither avalanche run-out zones not zones of active debris flow deposition (df). Also included are physiographic floodplain areas, areas of overlap between potential avalanche zones and slopes with thick colluvial overburdens (cst) or active colluvial slopes (csa), and all landslide (ls) areas not included in Category I.

Recommendations 2A (R2A)

Areas defined in Category II constitute a significantly reduced level of hazard compared with Category I in that slopes are potentially-unstable, with regard to both geologic and avalanche phenomena. Many of these areas are considered to be a delicate state of balance, which could be easily upset by improper management or use. Therefore, it is recommended that all development in Category II areas pay particular attention to factors of design and location of structures, excavation, and deforestation, so as to minimize physical impact.

Particular care is needed in the management of slopes where (cst) and potential avalanche hazards overlap since there exists a potential for snow instability and slope failure to a level that could endanger dwellings and access roads formerly regarded as hazard-free.

Landslide (ls) areas not included in Category I are potentially-unstable. The state of stability varies locally according to factors of slope and drainage and is impossible to evaluate without site studies, since more than one episode of landsliding appears to have occurred. It is probably erroneous to assume that the oldest features are the most stable. Also, attention should be paid to areas that have the same general characteristics as known landslide areas, but which do not appear to have undergone mass failure yet.

Any development of old landslide areas should pay particular attention to (1) drainage and irrigation; addition of large volumes of water through drainage division, irrigation and septic tank operation, may result in a localized mass failure of these deposits, even on relatively gentle slopes. (2) reduction of slope stability by excavation or construction; this may lead to a re-activation of landslide deposits of any age. Excavation of material near to the toe of a landslide deposit is ill-advised, since this reduces the magnitude of the force resisting motion on a slope. For the same reason, addition of material to the upslope part of a landslide deposit should not be carried out, since this increases the magnitude of the force driving the material downslope. Clearly, any combination of activities in (1) and (2) above may create a serious slope failure problem, which in the face of high mitigation costs, may necessitate abandonment of a site.

Recommendation 2B (R2B)

The debris fan areas in Category II involve a much reduced hazard over those in Category I, in that debris flow deposition does not appear to be a threat at present, and the areas so designated lie beyond avalanche runout limits. The Telluride incidents of 1914 and 1969 indicate that large, destructive debris flow events can occur on apparently 'inactive' debris fans. In fact the county seats of San Juan, San Miguel and Ouray are located on debris fans which have been active to a greater or lesser degree over the past 100 years. The events in this century on the Telluride fan justify the classification of the fan as Catgory I, although this probably reflects no more than the potential hazard level. However, the problem has not been evaluated from an hydraulic standpoint in this study.

Elsewhere along the San Miguel Valley, certain debris fan areas have been classed as Category II. It is recommended that the potential for both flood and debris flow inundation be investigated in these locations, since the Telluride events point to a high level of instability on the south-facing flank of the San Miguel Valley that may extent beyond the limits of the Cornet Creek catchment basin.

5.5: Category III

Included are all (cst) and (csa) slopes that do not overlap with potential avalanche areas, mine tailings (tail) and swamps (sw), and, also, areas of moderate colluvial activity (csm), expansive soil (es) and subsidence (sb) that are overlapped by potential avalanche areas.

Recommendation 3 (R3)

The precautions noted under R2A above, concerning the management of timber on potential avalanche slopes, apply here also in the case of overlap of this avalanche category with (csm), (es), and (sb) geologic hazard categories.

The bulk of Category III consists of (cst) and (csa) slopes that do not overlap with potential avalanche slopes. Management of (cst) slopes should take account of their potential instability with respect to mass failure. Slopes classed as (csa) constitute a somewhat different problem in that current instability affects only surficial soil for the most part. The rate of surficial erosion varies greatly across the (csa) category. In the most extreme case, headward erosion along gullies may undermine structures; also, surficial movement from sheetwash may cause thick soil deposits to accumulate on the upslope margins of buildings. Compaction of soils on (csa) slopes should be avoided, as this will reduce permeability and lead to greater runoff and surficial erosion than would otherwise have occurred.

The identification and avoidance of swamp hazard (sw) is considered to be sufficiently obvious not to warrant detailed treatment here. However, the possible adverse ecological effects of draining peat swamps should be noted. Compaction and wastage of peat occurs under these conditions, resulting in an overall lowering of the surface back to the newly-established water table.

Large mine tailings deposits are also readily identifiable. The case described in Section 3.2.11 should be borne in mind when construction is planned immediately downslope of such deposits.

5.6: Category IV

Included are all (csm), (es) and (sb) areas that do not overlap with potential avalanche areas; therefore, these areas are classed as avalanche-free, at the scale of mapping. Certain (es) areas may involve a high, local expansive potential from bentonite layers. These areas would belong to Category III, though have not been identified due to an absence of requisite stratigraphic information within San Miguel County.

Recommendation 4 (R4)

Apart from the local incidence of highly expansive bentonite layers within shale formations, there are probably few constraints on construction within this category. Nevertheless, it would be good engineering practice to test soil samples from proposed foundation levels, for their expansive properties in these areas.

As noted in the mapping legend in Appendix 1, (csm) areas may contain active colluvial or possibly potential mass failure zones which could not be depicted due to the scale of mapping.

5.7: Category V

This category includes all 'inactive' colluvial slopes (csi) that are free from snow avalanche effects at the scale of mapping. Subsurface factors, such as periodic high water table and corrosive soils (associated with acid mine drainage), should be studied in these areas. Close to the margins of expansive soil areas, (csi) soils should be tested for expansive properties.

Recommendation 5 (R5)

Since there appear to be few constraints on construction and transportation in this category, normal procedures of site preparation and construction should suffice. However, the safety of access routes should be considered carefully before authorizing any development, since the County may incur unreasonable responsibilities regarding road clearance and maintenance. For this reason, certain Category V areas may not be suitable for development.

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GLOSSARY OF TERMS

Angle of repose - the maximum gradient at which unconsolidated material will remain in place without sliding, governed by the internal friction and cohesion between particles

Argillaceous - like or containing clay

Bentonite - a clay formed from the decomposition of volcanic ash, largely composed of montmorillonite, and having a very high swell potential.

Cenozoic - the geologic era from approximately 65 million years ago to the present, which includes the Tertiary System, the last major Ice Age and the Post-glacial

Cirque - alpine landform of arcuate plan form at the head of a tributary valley developed by glacial overdeepening

Cohesion - mutual attractive force between small rock particles (e.g. clay minerals) in the presence of water

Colluvial action - the development of loose, poorly-sorted soil and rock waste from surficial processes such as rock-weathering, creep, and surface erosion, among others

Color-infrared film - reversal film which is sensitive to green, red and infrared radiation (.5-1.0 mm.) - also referred to as "false-color" because objects do not appear in their natural colors e.g. healthy vegetation appears red

Conglomerate - a sedimentary rock containing many rounded fragments larger than 2 mm., derived from fluvial, marine or glacial deposition

Contact - a junction plane between two rock-stratigraphic units

Creep - an imperceptible, slow, continuous downward and outward movement of soil or rock on a slope

Cretaceous - the geologic period from approximately 72 to 135 million years before present

Discharge - the volume rate of flow of water and sediment in an open channel

Edaphic - pertaining to, or controlled by local soil conditions

Fault - differential movement along a surface of rupture in a rock body

Felspars - commonly-occurring silicates of (principally) calcium and potassium

Fold - buckling of a rock unit from lateral compression

Formation - a rock-stratigraphic unit of distinctive composition (e.g. sandstone) or a distinct assemblage of members, that is mappable over a large area from its type section

Fracture - a line of rupture in a material, which may coincide with internal structural weaknesses e.g. cleavage.

Free-fall - the unimpeded fall of rock fragments under gravity alone

Glacial drift - material left by the retreat of a glacier, deposited by melting ice or glacial meltwater

Granodiorite - a coarse-grained, igneous intrusive rock

Gypsum - a hydrated sulphate of calcium

Hematite - an iron mineral often emplaced by hydrothermal alteration

Hundred-year floodplain - the area subject to inundation from a river flood with a statistically-averaged recurrence interval of 100 years

Hydrocompaction - a localized subsidence in materials of high silt content, caused by water saturation (e.g., irrigation).

Hydrothermal alteration - processes usually associated with the waning phases of igneous activity involving heated or superheated water, and capable of chemical alteration of rock through weathering and/or deposition of materials

Igneous - formed by volcanic action or intensive heat - rocks formed by the cooling and the solidification of magma

Illite - a commonly-occurring clay mineral subject to moderate expansion from water absorption

Intrusive - rock injected into surrounding rocks while in a molten state

Jurassic - the geologic period from approximately 135 to 181 million years before present

Laccolith - small to medium-sized igneous intrusive body that is concordant with strata into which it is intruded; usually, appreciable doming of strata results.

Laramide Orogeny - a mountain-forming event of late Mesozoic-early Cenozoic age

Levee - a raised linear deposit of unconsolidated material on either side of a debris flow channel

Limonite - a brown, hydrous iron oxide consisting mainly of the iron mineral goethite

Lithology - the mineral content and structural characteristics of a rock formation

Mass failure - the downslope movement of a large volume of rock and soil material generally over a short period of time (e.g. landslide, earthflow)

Mesozoic - the geologic era from about 230 to 65 million years before present comprising the Triassic, Jurassic, and Cretaceous Periods

Metamorphism - change in mineralogical, structural or textural composition of rocks under heat, pressure or chemical action

Montmorillonite - a clay mineral, also called bentonite, most subject to expansion by absorption of water

Moraine - material transported by ice and deposited as distinct landforms or fields of debris such as ground moraine

Oligocene - the geologic division in the middle of the Tertiary Period from about 25 to 36 million years before present

Outcrop - the area over which a particular rock unit is exposed at the earth's surface

Overburden - unconsolidated material which rests on solid rock

Oxidation - a process whereby oxygen from the air is combined with a mineral, leading to chemical breakdown to more stable minerals, e.g., limonite from iron

Palaeozoic - the geologic era from about 600 to 230 million years ago

Permian - the geologic period from about 220 to 280 years before present

Pleistocene - the geologic period from approximately 2 million to 10,000 years ago characterized by the Ice Age

Post-glacial - the period of time from the end of the Pleistocene to the present

Precambrian - the period of geologic time beginning with the consolidation of the earth's crust and ending with the start of the Cambrian period i.e. from about 4.5 billion to 600 million years before present

Quartzite - metamorphic rock formed by metamorphism of quartz sandstone

Quaternary - the younger of the two Cenozoic periods, comprising both the Pleistocene and the Recent epochs.

Remote sensing - the use of electromagnetic radiation to obtain information about a target at a distance.

Rotation - the movement of a mass of material along a curved plane

Series - a time-stratigraphic unit below the rank of a system

Shale - a sedimentary rock formed by the deposition of clay-textured material in water, subsequently metamorphosed, to a lesser degree than slate

Shear - applied stress which acts as a mechanical couple to produce angular deformation of a body

Slate - a hard, fine-grained metamorphic rock with well-developed cleavage formed by metamorphism of clay-rich parent rocks

Sheetwash - water which flows over a slope as an unchannelled layer, usually during a heavy rainstorm

Sill - an igneous intrusive body whose upper and lower boundaries are concordant with bedding in rocks into which it is intruded

Stereoscopic - a three-dimensional effect obtained by viewing two overlapping photographs using a stereoscope (a binocular optical instrument)

Stratigraphic - arrangement of rocks in layers due to deposition

Structure - the solid-geometric relations between rock-stratigraphic units determined by folding, faulting, etc.

Surficial deposits - unconsolidated materials of variable thickness e.g. glacial, landslide and river deposits

Tertiary - the system of geologic time between the Cretaceous Period and the beginning of the last major Ice Age, approximately 2 to 65 million years ago

Translation - the movement of a mass of material relative to a fixed reference point, generally across a flat plane

Triassic - the period of geologic time extending from about 225 to 195 million years before present, between the Permian and Jurassic Periods

Tuff - a consolidated volcanic ash

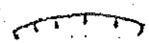
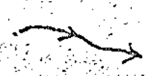
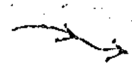
Viscosity - the property of a fluid that determines its rate of flow under externally-applied stress (shear)

Yield strength - or elastic limit - maximum stress a specimen can withstand without undergoing permanent deformation by either solid flow or rupture

APPENDICES

APPENDIX 1

GEOLOGIC HAZARD LEGEND

Category and map abbreviation	Description of Category
1. Rockfall (rf)	Source areas for falling rock. Includes potential rockfall areas.
2. Rock glacier (rg)	Area affected by the slow downslope creep of talus, generally due to the presence of an ice core.
3. Landslide (ls)	A large-scale failure of slope material involving surficial and/or rock. Failure may involve rotational slumping, shallow faulting, flow, and translation of material along inclides shear planes. Sub-category:  Active or recently active slip faces.
4. Expansive soil and rock (es)	Areas of clay-rich, cohesive soils, derived mainly from clay and shale formations. Significant volume changes occur during cycles of wetting and drying. Due to the scale of mapping, areas so defined may include rock outcrops which are not expansive (e.g., sandstone).
5. Talus slope (ts)	An area of active deposition of material from rockfall and debris flow. Mass failure may occur as talus slides or debris flows. Sub-categories: Talus slide (tss)  Active or recently active debris flow tracks.
6. Debris fan (df)	A flattened, cone-shaped deposit which accumulates from repeated deposition of stream flood and debris flow material at the exit point of a tributary stream into a larger valley. Sub-category:  Active or recently active debris flow tracks.

APPENDIX 1 (continued)

Category and map abbreviation		Description of Category
7. Colluvial slopes		
	Sub-categories:	
	cst	Areas of thick colluvial or glacial accumulations, generally thicker than six feet. Potential mass failure areas.
	csa	Areas of accelerated colluvial activity on slopes where deposits are less than six feet thick.
	csm	Areas of moderate colluvial activity on slopes where colluvial deposits are less than six feet thick.
	csi	'Inactive' colluvial slopes, having slight colluvial activity on slopes less than 15 percent, having deposits less than six feet thick.
8. Physiographic floodplain (pf)		An area experiencing frequent erosion and deposition from streamflow. Areas defined probably encompass most of the 100-year floodplain but mapping is not based on stream discharge records.
9. Swamp (sw)		Areas subjected to seasonal or longer-term inundation from high water table conditions.
10. Subsidence (sb)		Areas subject to collapse of surficial material and/or bedrock due to removal of subsurface fluids, or removal of subsurface rock by solution or mineral extraction.
11. Tailings (tail)		Large deposits of rock waste from a milling operation which occur either as large pond deposits or as steep cones on slopes.

APPENDIX 2

SNOW AVALANCHE HAZARD LEGEND

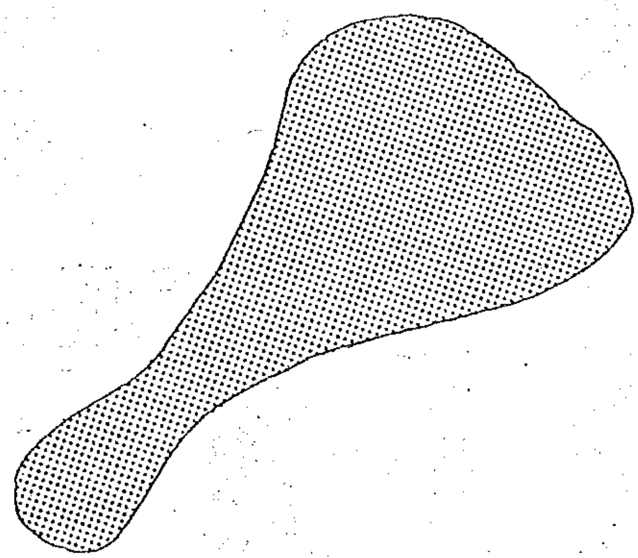
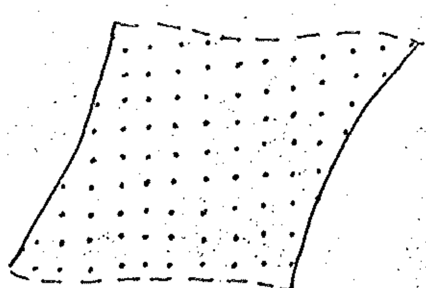
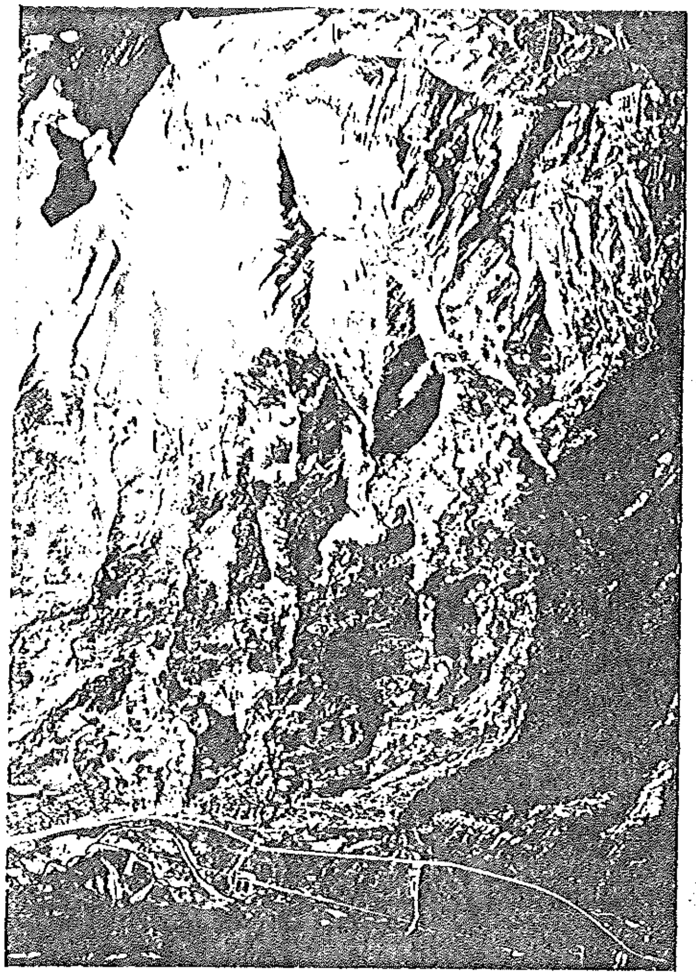
Category and map symbol	Description of Category
	1. Active snow avalanche path. Also includes unvegetated slopes above timberline steeper than 60 percent.
	2. Potential avalanche area. All slopes steeper than 60 percent that are timbered and bear no clear signs of avalanche activity at the present time. Applies only to areas above 7,000 ft elevation.
	3. Small avalanche path that cannot be depicted by (1) above, due to the scale of mapping.

Plate 1: Segment of color infrared frame from Mission 213, Roll 59. The San Miguel Valley, between Telluride (bottom right) and Society Turn is depicted. The layered succession of rocks in the high peaks is the Gilpin Peak Tuff, below which large amount of talus and rock glaciers have accumulated. Timberline co-incides roughly with the contact between the San Juan Tuff and the underlying Telluride Conglomerate. The Telluride Formation is exposed in rocky cliffs just below timberline. Much of the forested slope below is underlain by the Mancos Shale or Cretaceous age. Small landslides have occurred at the contact with the overlying Telluride Formation.

A change in texture occurs just above Highway 145, at the extreme left of the picture, where the Mancos gives way to a rocky debris slope formed by rockfall from the Dakota Sandstone and the Morrison Formation. The light band above the Highway at the right of the picture is formed by an outcrop of the Dolores Formation, the basal part of the gullied slope being formed by the Cutler Formation. Large flattened debris fans occur at the exit points of Eider Creek and Mill Creek, near to the settlement of San Miguel. Recent flood and debris flow deposits can be seen. Finally, the physiographic floodplain of the San Miguel River crosses the picture from right to left at the bottom.

Plate 2: Segment of a color infrared frame from Mission 247, Roll 2 depicting the area of the confluence of the South Fork of the San Miguel River and Howard Fork at Ophir Loop. Trout Lake and Lizard Head Pass are at the bottom left. The mountainous areas at the right of the picture are Yellow Mountain, at the bottom, and the Ophir Needles, at the top. A difference in texture of weathering and degree of talus accumulation can be seen between the two areas, the first underlain by Tertiary volcanics, the second by Tertiary intrusives. The mountainous area at the left of the frame is San Bernardo Mountain, from which several large avalanche paths descend to Lake Fork. Distinct trimlines are also visible within coniferous forest cover on the south side of Howard Fork.

The area of mottled texture to the right (east) of Trout Lake is underlain by the Yellow Mountain landslide, caused by movement of Tertiary material across the Mancos Shale. The Mancos is exposed to the southwest of the Lake and forms much of the terrain between the Lake and Lizard Head Pass.



<u>Plate 3:</u> The small debris fan located between Cornet Creek and Owl Gulch, in northeast Telluride. The fan is constructed below cliffs in Mesozoic formations, principally, the Dolores, Entrada and Wanakah. The rock face is freshly weathered, indicating that rockfall may present a hazard at the present time. Blocks are scattered across the steep slope above the debris fan. The debris fan does not bear recent evidence of debris flow deposition, primarily because the catchment of this un-named gulch is extremely small and does not extend into unstable areas above timberline.

<u>Plate 4:</u> Steep, un-named gulch and debris fan on the east side of Bear Creek, south of Telluride. This is an instance of overlapping geologic and avalanche hazards; large slabs of rock have detached from above and have slid across a talus slope composed of finer material, including debris flow deposits on the fan. Also, swaths cut through the coniferous timber at the upper left corner of the picture attest to the presence of avalanche activity in this location. The debris fan is also an avalanche runout zone.

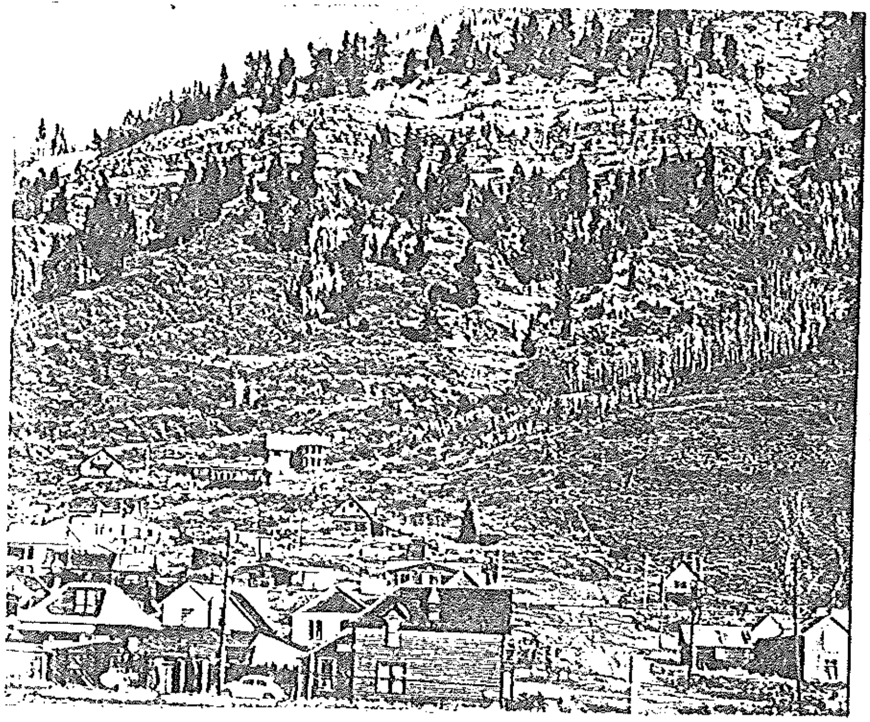


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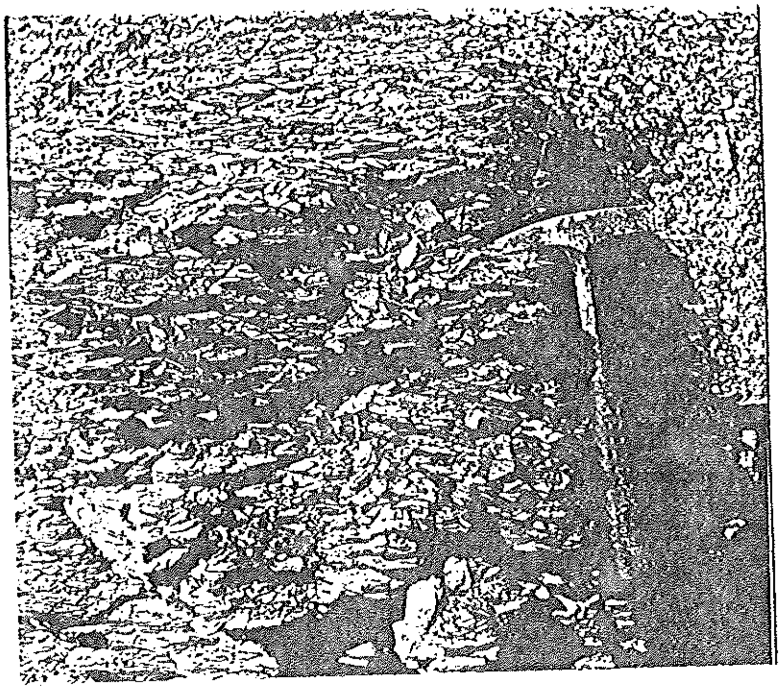
Plate 5: Exposure of the Mancos Shale, indicating the highly fissile nature of the shale. This lithological characteristic produces numerous lines of weakness, resulting in a low mechanical strength and a rapid rate of weathering. The impermeable nature of the formation produces instability in overlying porous formations, since the interface with the Shale is usually a line of groundwater seepage.

Plate 6: Close-up of expansive soil derived from the Mancos Shale. (Quarter gives the scale). Polygonal tension cracks develop when the soil dries out and shrinks. The reverse process of swelling and crack closure occurs when the soil is wetted.



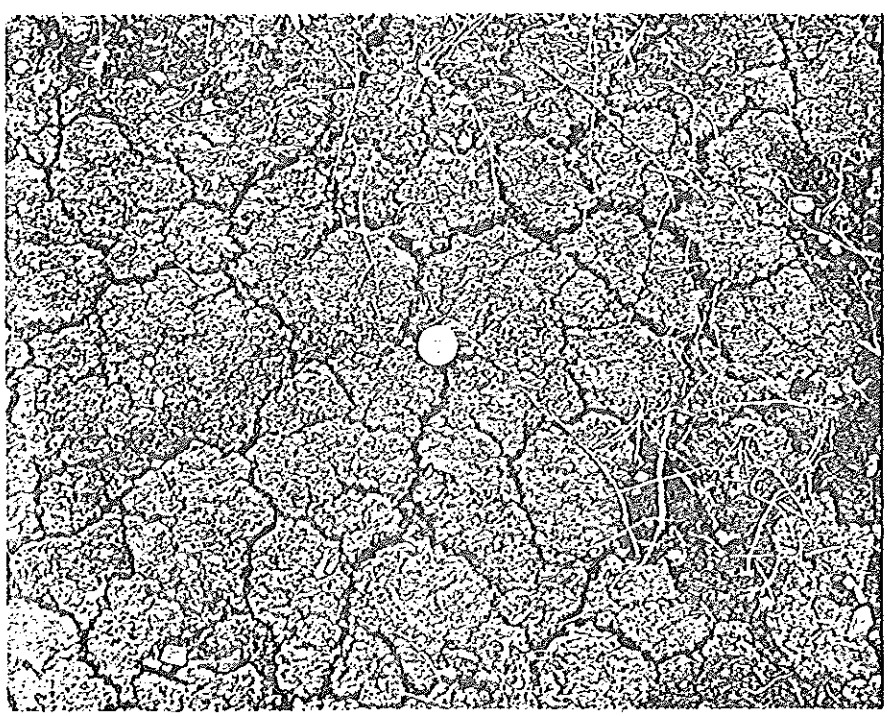


Plate 7: Rockfall and talus slopes developed from Tertiary volcanic outcrops on the San Miguel County side of Ophir Pass. The columnar structure is typical of eroded tuffs and breccias. Zones of higher than average activity on the talus appear as lighter zones, since the lichen cover is interrupted. These zones are small talus slides, probably produced by a locally-accelerated rate of rockfall. In addition, large open-slope avalanches occur in this area in winter and run down to Howard Fork below.

Plate 8: Debris flow tracks in the headstreams of Spring Gulch, above Old Ophir. The main axis of the Gulch is filled with talus material which probably derives from debris flow deposition and talus slides. This picture is typical of many high, alpine basins in eastern San Miguel County that head into volcanic rocks of the Potosi Group.

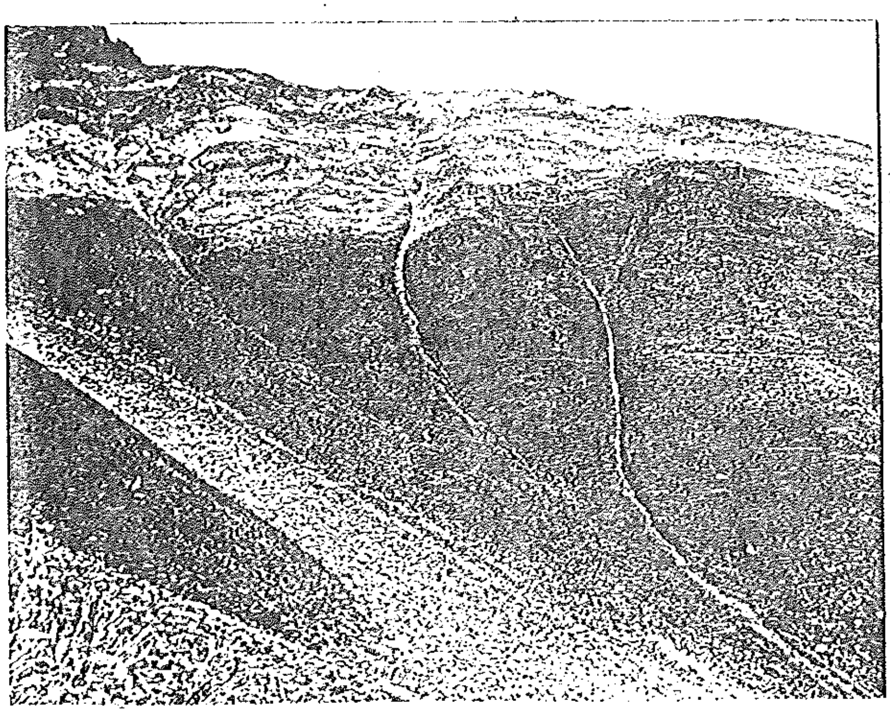
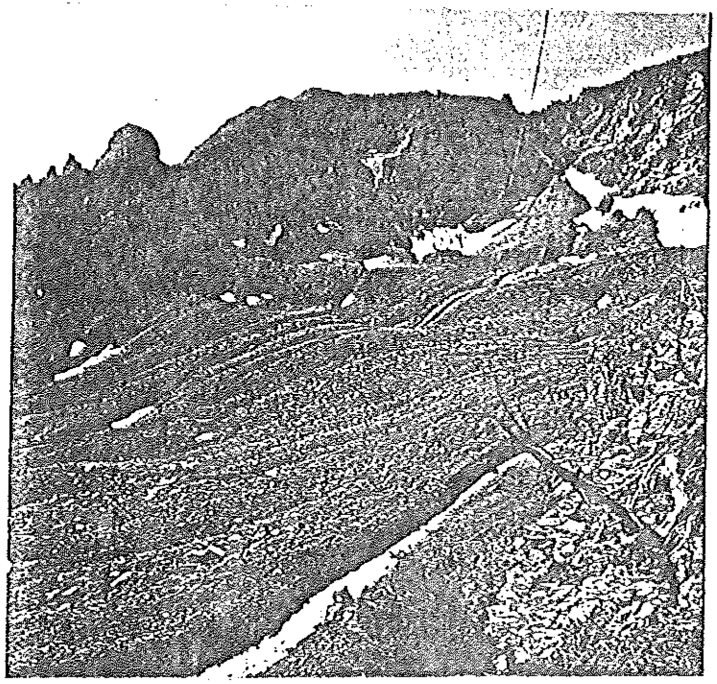


Plate 9: Large rock glacier, descending from steep, unstable, Tertiary volcanic terrain which surrounds Silver Basin, above Camp Bird, Ouray County. The ridge is the county line with San Miguel County. The gradation of the rock glacier into the flanking talus deposits is evident. Lichen cover on many of the boulders on the surface of the rock glacier indicates that this feature may be moving only slightly at present.

Plate 10: Slope failure about 50 yards across, close to the Last Dollar Road on Hastings Mesa. Failure has occurred in glacial material overlying Mancos Shale. These features are not uncommon in the northern plateau county of San Miguel and Ouray counties; older features have less well-preserved scarps and toe areas. The area below the scarps is now being deepened by gully erosion. This example indicates that, given the right combination of circumstances, thick glacial or colluvial accumulations can fail on only moderately-steep slopes, particularly if underlain by the Mancos Shale.



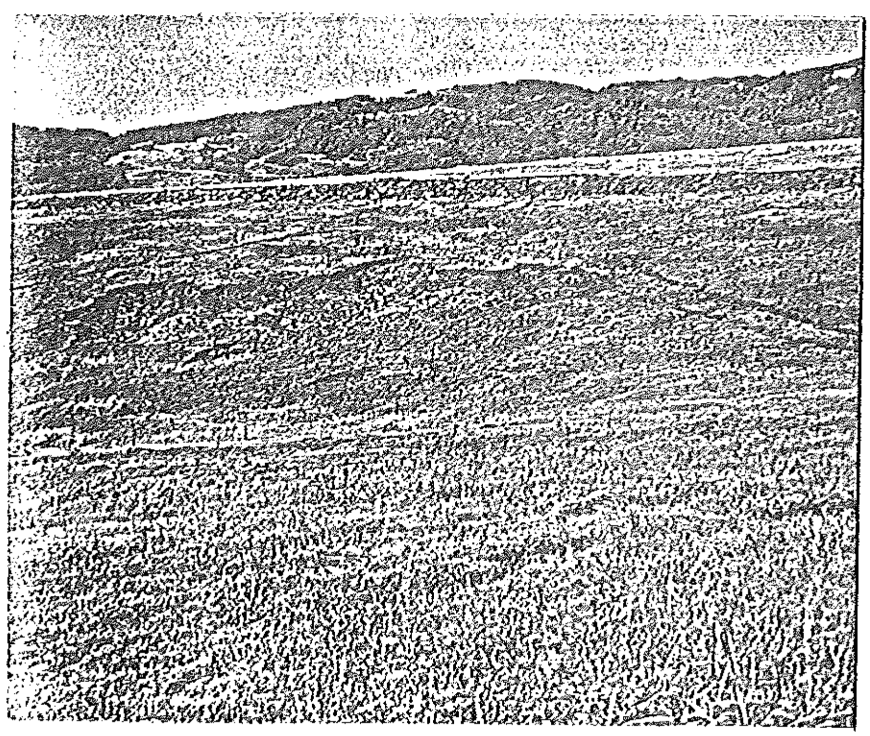


Plate 11: Large active landslide on the south side of Cedar Creek, Montrose County, close to U.S. Highway 50, about nine miles east of Montrose. The crown of the slide indicates repeated step-faulting of the Mancos Shale, below which failed mass spreads out by flow and sliding. Failure of this area is due to porous river gravels sliding over the Manoos Shale in a zone of groundwater seepage at the tratigraphic contact between the two formations. Seepage is still active at the head of the landslide and is causing active recession of the headwall.by slumping.

Plate 12: Roadcut in glacial and landslide material, on the west side of the Silver Mountain landslide, just north of Ophir Loop on Highway 145. Some impression is given of the great thickness of the glacial/landslide debris in this area. Disruption of the road surface out of the field of view indicates that deeper seated movement is occurring, in addition to slipping of material on the cut face.

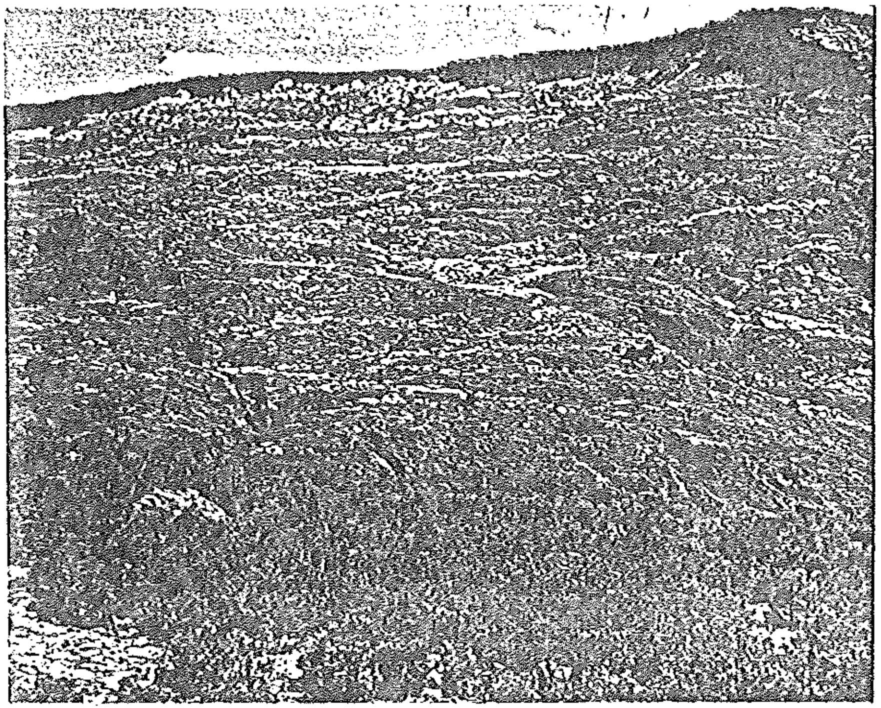


Plate 13: Low-level aerial oblique of Spring Gulch and Staatsburg Basin, on the north flank of Howard Fork. Trimlines in both aspen and coniferous cover are clearly visible at the left part of the picture and demarcate the Badger group of slidepaths. The Spring Gulch avalanche runs onto the large debis fan; just above the apex, a double trimline in aspen is seen, which roughly differentiates large from small avalanches. Avalanche debris from the previous winter follows the axis of the Gulch. The stream course which skirts the right side of the fan is followed, periodically, by large, wet avalanches in spring, yet also have been recorded as traversing the center of the fan to Ophir, the small settlement at the bottom of the picture. Large powder avalanches are thought to impinge on the adverse slope (bottom of picture) about five times each century.

The lighter zones on the debris fan surface are caused by dry soil conditions in the crestal areas of large debris flow levées. From their pattern, it is seen that every part of the fan has experienced debris flow deposition in the past. All of the features are vegetated, yet still preserve the topographic form of levees. The age of the levées is unknown. However, no fresh deposits exist on the fan.

Plate 14: Debris fan developed below Tertiary volcanic cliffs on the south flank of Howard Fork, just east of Ophir Loop. Vegetated debris flow deposits are seen on the surface of the fan. Avalanche trimlines are seen in coniferous vegetation on either side of the debris fan. Aspen trimlines are inset within the coniferous limits, indicating partial colonization of the large avalanche track. The central zone which lacks trees is the zone of most frequent avalanching.

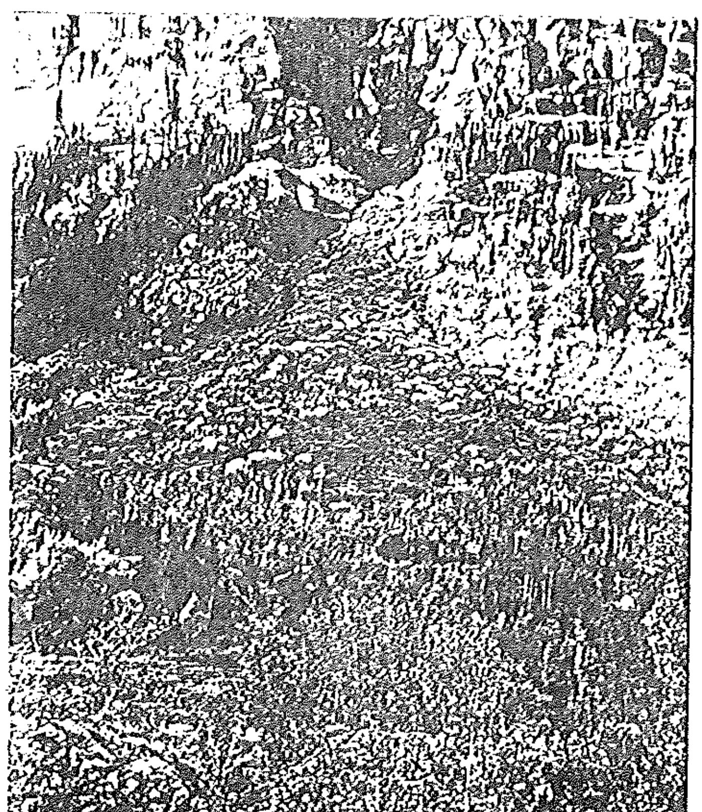


Plate 15: Damage from the 1914 debris flow inundation of Telluride by Cornet Creek. The peculiar character of debris flow material enables it to support the weight of large blocks of rock, which may inflict considerable damage to structures. The photograph was taken after the debris had been cleaned up, so that the pile in the foreground is not the terminal surface of the original debris flow.
(Photograph courtesy of the San Miguel County Museum, Telluride).

Plate 16: Color infrared frame from Mission 247, Roll 2, encompassing the valley of Howard Fork, running past the large debris fan illustrated in Plate 13, and the valley of Waterfall Creek, running from the bottom of the plate to the Ophir townsite. Due to color shift on the infrared film, all vegetation appears red. Aspen (in full leaf) are differentiated from coniferous species by their bright red color, The light red is grassland.

The change in life-form between grasses and deciduous or coniferous vegetation, enables avalanche paths to be easily detected on this type of film. The double trimline between younger and older aspen is clearly seen at the apex of the Spring Gulch debris fan. A considerable number of large paths descend to Waterfall Creek. The narrowest tracks in Howard Fork valley are depicted by arrows on the avalanche hazard maps.

Plate 17: Avalanche impact damage from dry avalanches on the adverse slope of the Spring Gulch avalanche path, at Ophir (See Plates 13 and 16 for the general setting). Limbs have been trimmed from the sides of the trees exposed to impact and many trees have been felled on the adverse slope. This is clear evidence of periodic avalanche activity on a large scale.

Plate 18: Flow-aligned timber debris deposited on the debris fan of Spring Gulch, just above the Ophir townsite (middleground). The debris is most probably derived from wet flowing and (partly) from dry flowing avalanches. The debris extends almost as far as the townsite, yet on all parts of the fan, the debris limits are within the probable maximum runout limits deduced from impact evidence (Plate 17). Also, the debris is confined to lower areas between the debris flow levées on the fan; however, it is now fairly-well established that flowing and airborne snow affect large areas of the fan and are not constrained by minor topographic irregularities. For that reason, this type of field evidence must be interpreted with caution and, if possible, supplemented with other types of information. Where this is not available, debris usually provides only a first approximation to the maximum runout area, and invariably underestimates this area.