Geographic information systems applied to rock slope stability analysis in Yellowstone County, Montana
by Edwin Jay DeYoung

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
There are over 200 mapped slope failures in Yellowstone County, Montana. This study uses Geographic Information Systems (GIS) analysis to predict slope-failure hazard. Most regional slope stability analyses do not address discontinuity factors although such discontinuities are widely recognized as important. This analysis tests the importance of bedding-plane discontinuities in Yellowstone County.

Data layers consist of ARC/INFO grids with values of slope gradient, material type, slope type and the distance to the nearest lithologic contact for each 30 meter cell of the study area. Average slope gradient was calculated from U.S. Geologic Survey 30m Digital Elevation Models. Material type was categorized as the dominate lithologic material (sandstone, shale or mixed) in each cell area. A surface was created from near surface structure to represent bedding layers parallel to lithologic units. Slope type was determined from the relative structure gradient (dip) and slope gradient, identifying key areas having similar structure orientation and slope aspect. A stepwise discriminant analysis was used to determine the combination of slope, material, slope type and contact distance factors to determine the combination of variables to maximize the difference between mapped landslide locations and a set of stable slope cells.

Slope gradient is the strongest discriminating factor, and accounts for nearly 80% of the variance in the discriminant function. Material type has minimal significance and slope type is insignificant in discriminating between failed and stable slopes in this study. The distance to contacts with relatively hard lithologic units overlying relatively soft lithologic units is significant in discriminating between failed and stable slopes, accounting for nearly 20% of the discriminant variance. The origin of these relationships is probably related to mass movement.

Bedding discontinuity is a relevant factor although bedding is not a significant factor as determined for this study area. Overdip slope types are likely misclassified because the cell size (±250 m) approaches the size of mass-movement features. Site analysis shows discontinuities are a part of overall instability analysis, however, further work is needed to successfully incorporate bedding discontinuities in a regional stability analysis.

The probability of rock slope failure was determined for southern Yellowstone County, Montana from slope gradient, material type and the distance to the nearest hard over soft contact. This study does not give any site-specific information because input data was averaged to 30m grid cells and the resolution of combined analysis of multiple data sources is ~250m. The results indicate slope-failure probability for general areas. The maps can be used for regional assessment and emphasize where site-specific analysis is strongly recommended before development.

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APPROVAL

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Edwin Jay DeYoung

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ABSTRACT

There are over 200 mapped slope failures in Yellowstone County, Montana. This study uses Geographic Information Systems (GIS) analysis to predict slope-failure hazard. Most regional slope stability analyses do not address discontinuity factors although such discontinuities are widely recognized as important. This analysis tests the importance of bedding-plane discontinuities in Yellowstone County.

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CHAPTER 1

INTRODUCTION

Statement of Problem

Slope failure is a widespread natural hazard that poses a threat to life and property. Such failures are a problem in Yellowstone County, Montana (Yellowstone County Department of Planning, 1990). Assessment of where slopes are unstable is necessary for planning future development. Such planning would enhance opportunities to avoid building on unstable sites or encourage special design where building does occur in such cases (National Research Council, 1985). One approach to locating potentially unstable slopes is through analysis of slope instability factors through Geographic Information Systems (GIS) technology in Yellowstone County.

Figure 1.1 outlines the components addressed in this thesis on slope stability analysis. The pyramid structure represents stability prediction as the culminating goal. Identification of factors critical to slope stability is fundamental to the analysis. After the factors are identified, sources of information about the factors are collected. Collected data is imported into a GIS format. GIS is used to calculate derived layers which give additional information specific for slope stability analysis. Statistical analysis of data representing the determined factors allows prediction of potential slope instability for the study area.

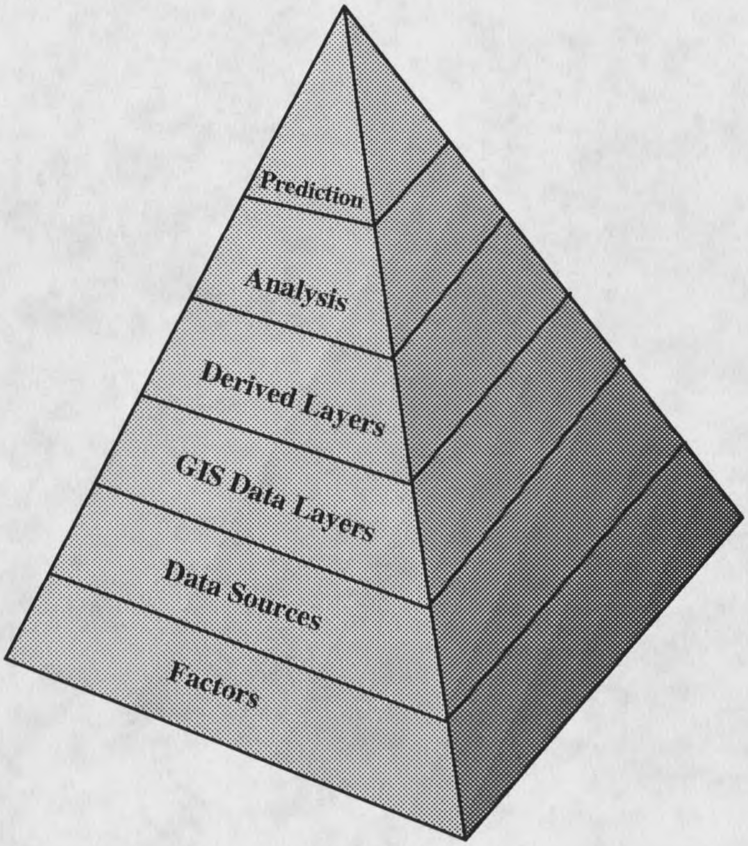


Figure 1.1. GIS model for prediction. Pyramid diagram shows order of model process from factor basis to final prediction.

GIS enables the processing of input data and the spatial analysis to evaluate locations of potential slope failure. Representation and analysis of multiple factors through space is feasible in GIS. Identification of appropriate land stability factors is fundamental for analysis and accurate predictions. Past GIS models have used factors of slope and material type but have generally left out geologic discontinuities. A model that incorporates such discontinuities is expected to better predict the location of unstable slopes than a model using slope and material alone. GIS technology enables rigorous instability analysis for large data sets for county sized regions, and is cost effective.

Study Area

The study area is the southern two-thirds of Yellowstone County, Montana (Fig. 1.2), where detailed elevation data are available. Billings, the most populous urban center of Montana, Laurel, several smaller towns and part of the Crow Indian Reservation are in the study area. The Yellowstone County Comprehensive Plan (Yellowstone County Planning Department, 1990) identifies slope stability as an important environmental geologic factor for planning and development. Three stated goals of the plan are to encourage designs which respect existing topographic features, take natural physical constraints into consideration, and promote safety in existing and new residential development. The aim of the county plan appears to be to inform residents of the existing natural hazards and to promote informed rational decisions about suitability for development.

This study will not provide the detailed information that is needed on a site-specific basis to make an informed decision about slope instability hazard. Rather, the intent of this study is to promote slope stability as a necessary consideration for development evaluation potential and indicate where site evaluations are critical for responsible development at a county-scale. More detailed site evaluations will be necessary because slope gradient, material type and all other slope characteristics vary at scales finer than 30 m x 30 m (the grid scale of the largest-scale GIS data layer).

Difference in topographic elevation is one of the bases for potential slope instability (Fig. 1.3). Overall relief in the area is 650 meters. The Pryor Mountains form a high area (1,518 m) at the southern edge of the study area. The lowest point (867 m) is in the northeast corner of the study area along the Yellowstone River. Elevation differences in Yellowstone

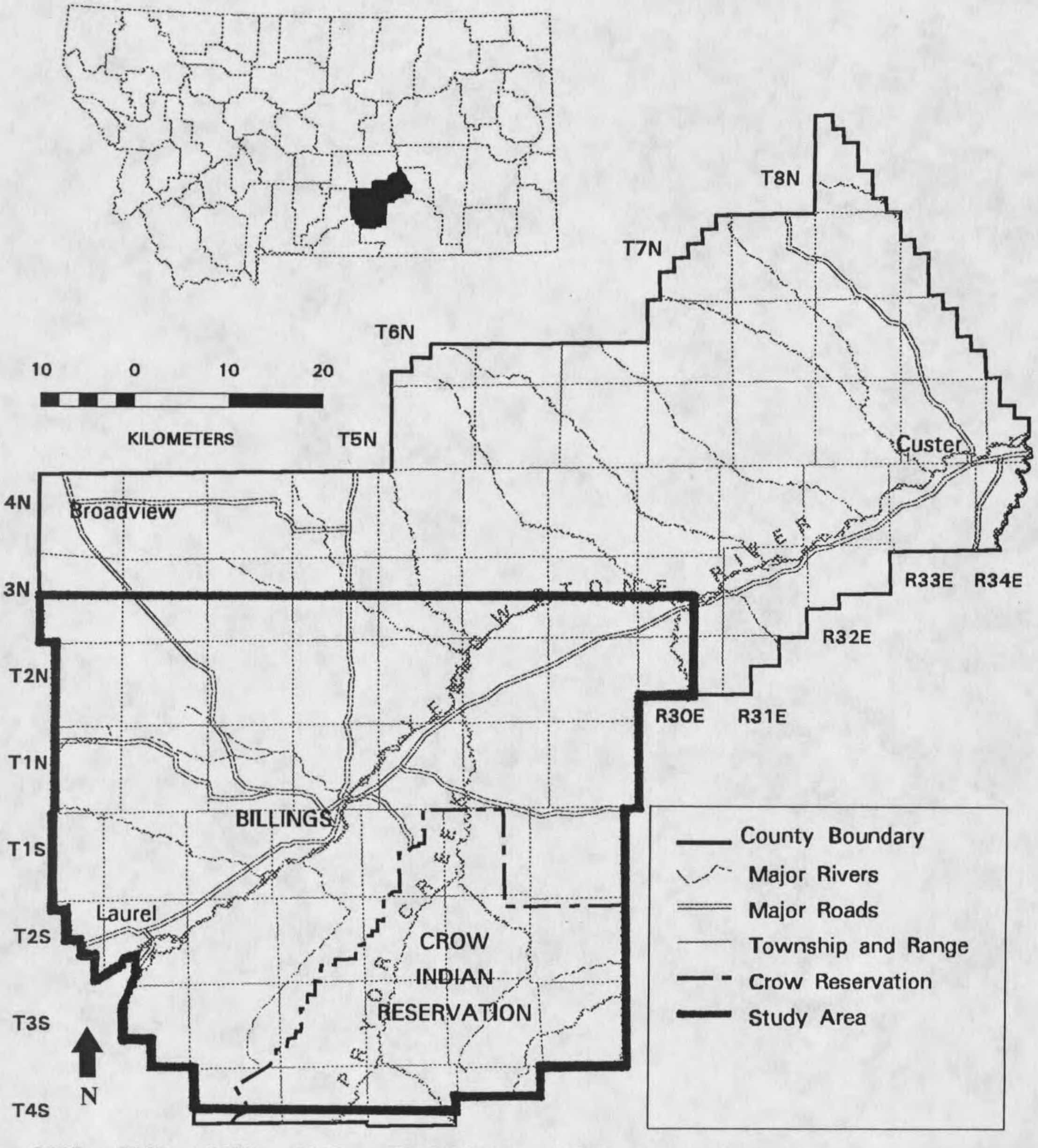


Figure 1.2. Location of study area within Yellowstone County, Montana.

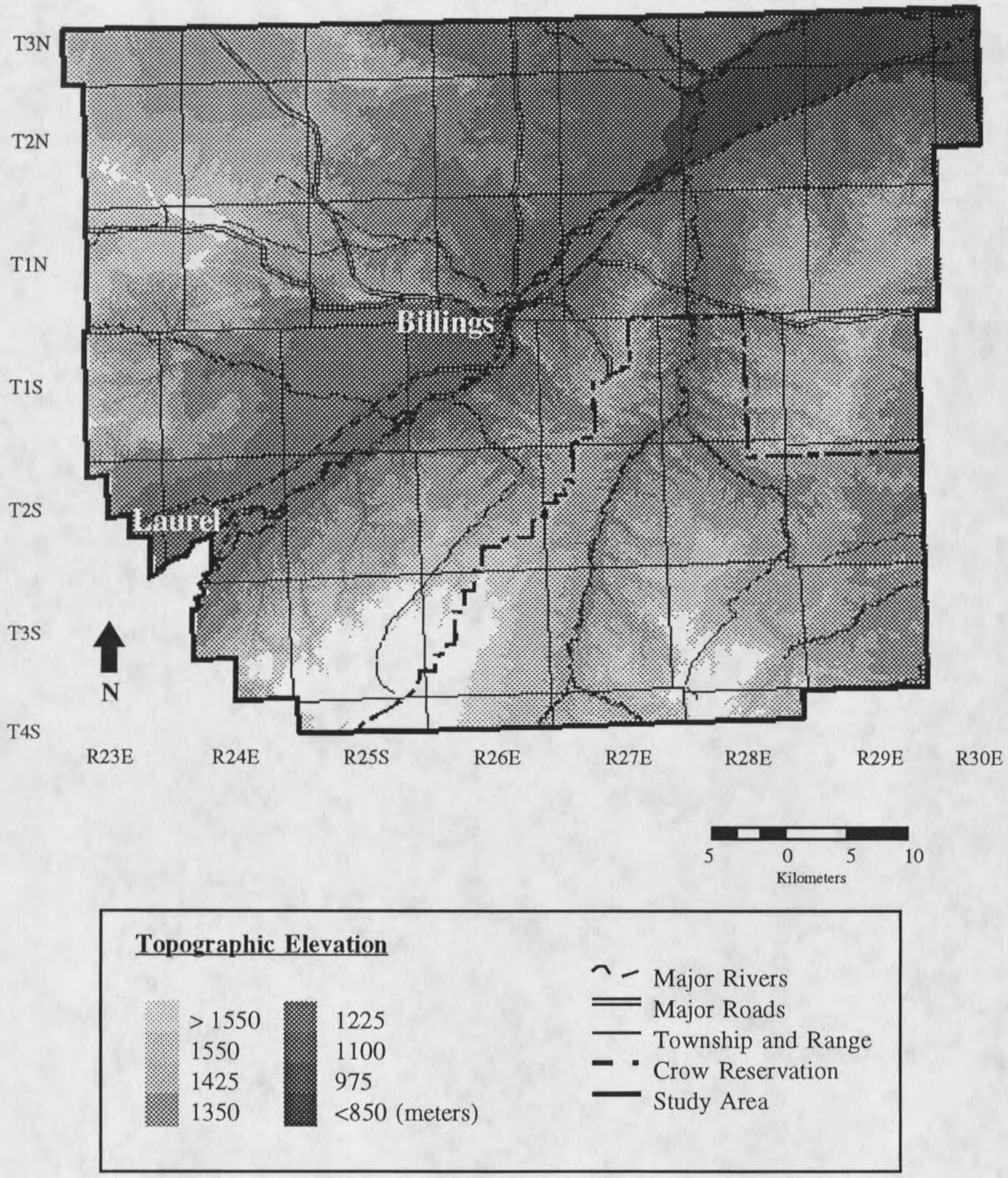


Figure 1.3. Topographic elevation.

County create potential for valley dissection, especially along Pryor Creek and its tributaries. Such tributary dissection forms steep slopes conducive to mass movement.

Topographic transitions from high to low areas are stepped due to alternating weak and strong Cretaceous shales and sandstones (Fig. 1.4). Resistant ridges and cliffs form in sandstones while gentle slopes and basins typify shales (Thom, 1935). The bedrock in the study area is Cretaceous in age. The Cloverly Formation, outcrops in a small area at the center of the southern edge of the study area (Fig.1.5). Moving up the stratigraphic column, the younger Cretaceous rocks of the Colorado Group outcrop north of the Cloverly in the southern part of the study area. The Montana group lies above the Colorado Group and outcrops to the north from near the southeast corner of the study area to the northern edge of the area. The Lance Formation, above the Montana Group, is the youngest Cretaceous formation in the study area and outcrops only in small areas along the northern edge of the study area. Tertiary gravel tops the butte rising above the Quaternary material in the southwest corner of Township 1 south, Range 24 east (Fig. 1.5). Quaternary sediments occur as fluvial deposits, terraces and fans along the Yellowstone River valley and as marsh sediments in the Comanche Basin near the northwest corner of the study area.

The geologic formations dip gently to the north off of the Pryor Mountain uplift at the southern margin of the study area. The dissected plains are formed on the layered Cretaceous sandstone and shales, which are stepped due to differing weathering rates and dissected by river tributaries. The Lake Basin and Fromberg fault zones locally complicate the geology (Fig.1.6). Topography reflects the combination of lithology and structure.

ERA	PERIOD		FORMATION	MEMBER		DESCRIPTION	CLASS
CENOZOIC	QUATERNARY				Qt	Gravel, Sand, Clay	
	TERTIARY				Tt	Gravel, Sand	
MESOZOIC	CRETACEOUS		Lance		Kl	Sandstone, Clay	Mix
		Montana Group	Lennep		Kle	Andesitic Sandstone	Ss
			Bearpaw		Kbp	Dark Marine Shale	Sh
			Judith River		Kjr	Interbedded Ss, Shale	Mix
			Claggett	Parkman	Kcp	Sandstone	Ss
					Kcg	Shale, Sandstones	Sh
			Eagle		Ke	Massive Sandstone	Ss
			Telegraph Creek		Kte	Sandy Shale, Sandstone	Mix
		Colorado Group	Niobrara - Carlile		Knc	Shale, Minor Sandy Beds	Sh
			Frontier	Torchlight	Kft	Sandstone	Ss
					Kf	Shale with thin Ss	Sh
			Mowrey		Km	Shale, Bentonite Zones	Sh
			Thermopolis		Kt	Shale Muddy Sandstone Shale	Sh
			Cloverly	Greybull	Kg	Sandstone	Ss
					Kcl	Volcanic Ash Chert Conglomerate, Ss	Sh
	JURASSIC		Morrison		Jm	Shale, Sandstone	

Figure 1.4. Stratigraphic column for south central Montana (From Knappen and Moulten, 1930, p.8-9). Symbol and description are given for every formation and prominent member in study area. Sandstone (Ss), shale (Sh) and mixed lithology (Mix) classifications shown are used in the analysis. The dashed line represents an unconformity, however, the Morrison outcrops just south of study area.

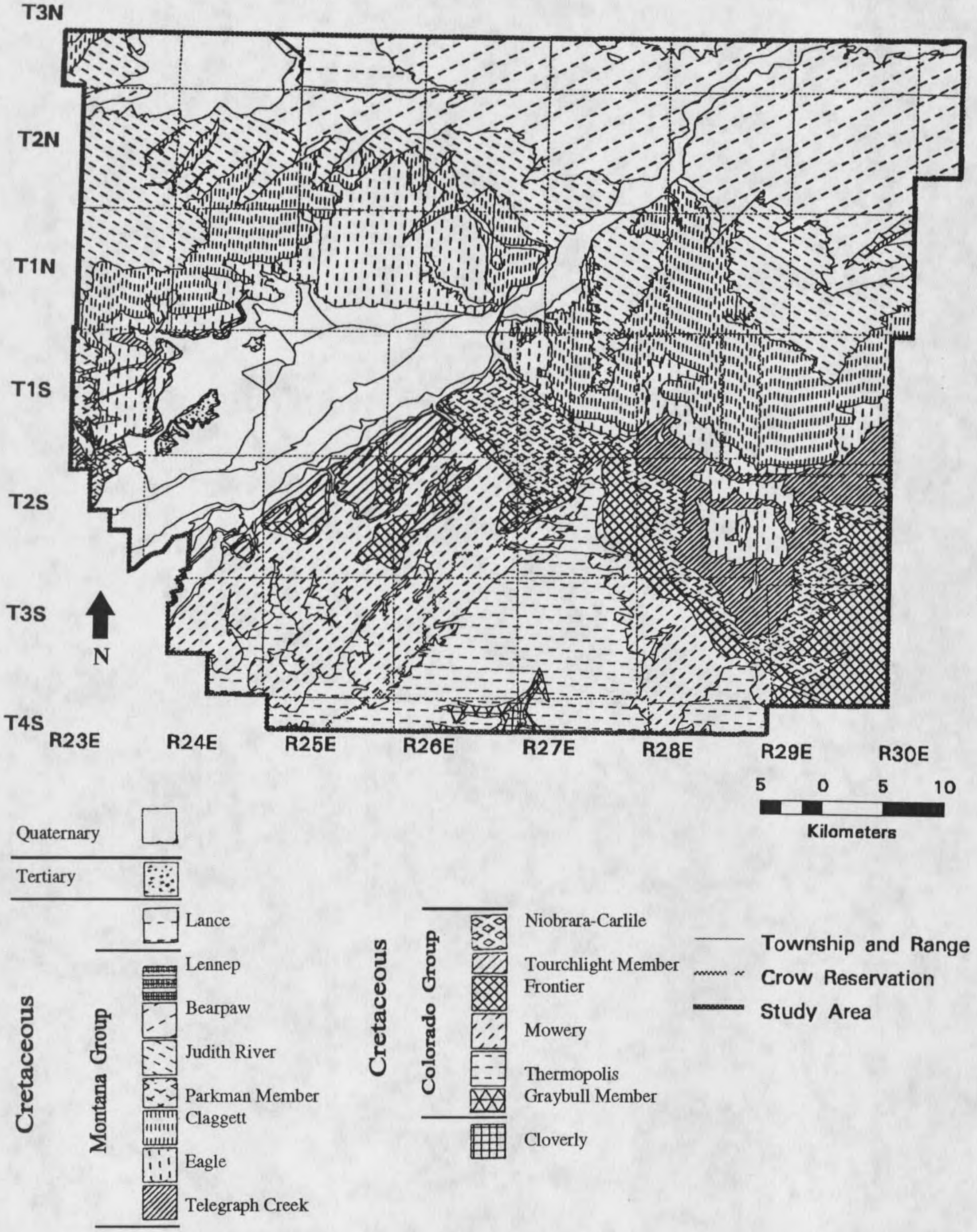


Figure 1.5. Geologic map of study area.

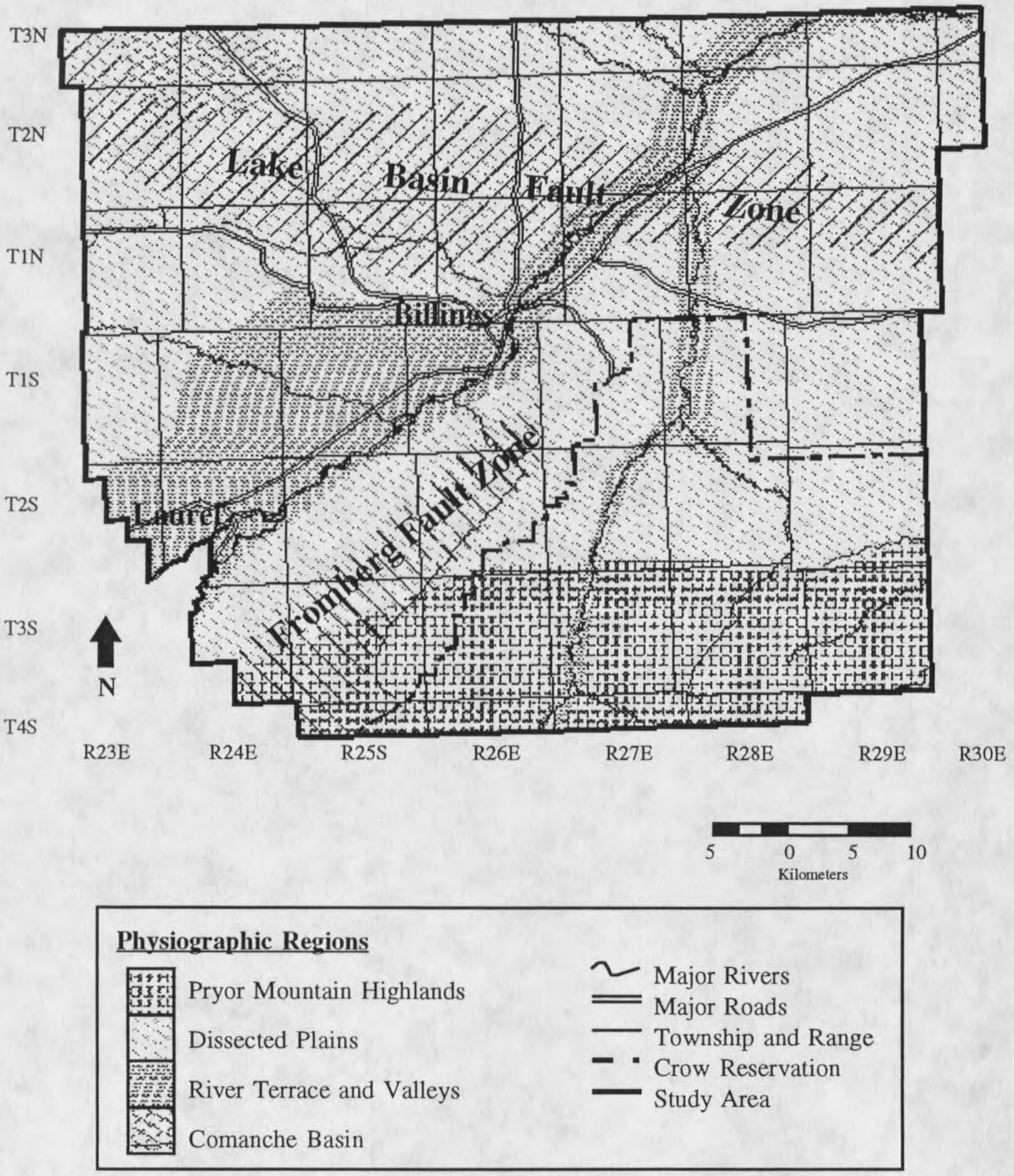


Figure 1.6. Physiographic regions and fault zones.

Slope instability hazard exists throughout the county because of the varying relief of the dissected topography on rocks of varying strength.

Review of Relevant Literature

The only published slope stability hazard analysis of Yellowstone County is included in a Montana Landslide Hazard Map (Fig. 1.7; Mills, 1987). Mills' (1987) map was produced using slope, geology and precipitation factors for cell areas of 21 km^2 (8 mi^2). Most of Yellowstone County has a moderate slope failure hazard according to Mills, but slope failure is locally recognized as an important consideration for development in the Yellowstone County Master Plan (Yellowstone County Department of Planning, 1990). A more detailed representation of the variability at the county scale is needed for slope stability analysis and planning in Yellowstone County.

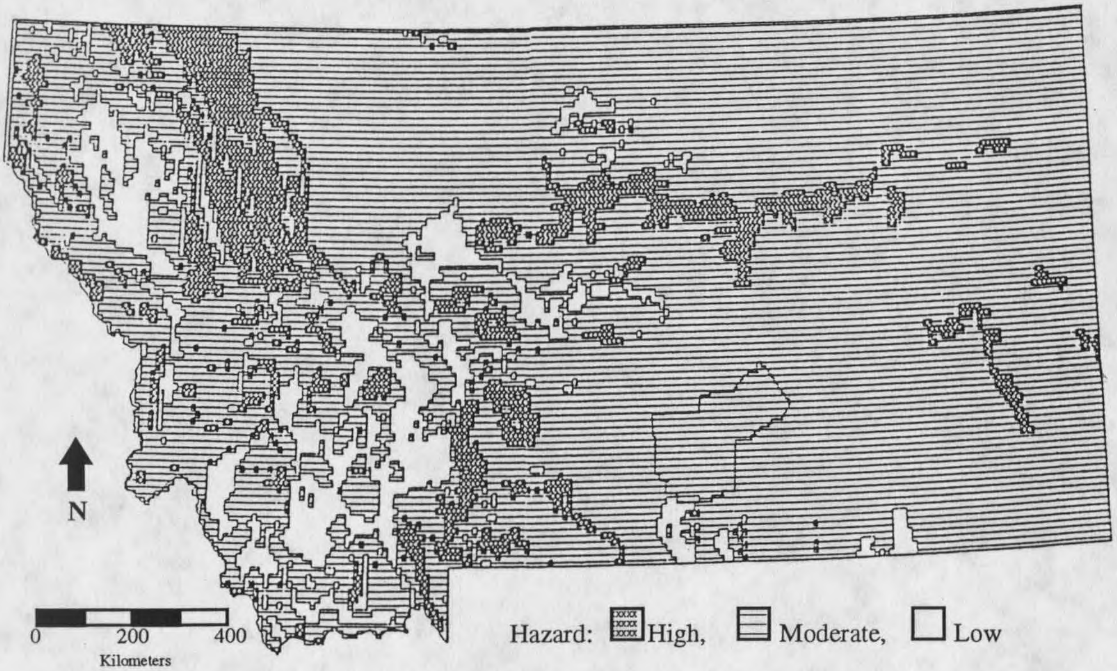


Figure 1.7. Landslide hazard map of Montana (After Mills, 1987). Outline of Yellowstone County shown.

One source of information on slope instability comes from a preliminary map of landslides in Montana (Wilde and others, unpublished, Fig. 1.8) which shows the location of 200 landslides in Yellowstone County. This map compiles the location of failures reported in the media and scientific literature. The data base associated with failure locations gives the source of the data but no failure type information. Small events of a few cubic meters, like the rockfalls along the Rimrocks (Eagle Sandstone) in Billings, are not included in the database even though they are known to occur.

Most small rock failures in the region are likely to be topples, but large failures are slides and, to a lesser extent, slumps. In incompetent rocks (like the Cretaceous section!) Both slumps and slides transition to flows downslope, regardless of water content. The hazard from slumps, slides and flows is similar in that all tend to be restricted to a fall/flow ratio of greater than 0.4, but the risk certainly varies from place to place depending on lithology and orientation of discontinuities.

Based on the map of landslide occurrence (Fig. 1.8), the slope stability hazard is not uniformly moderate. Past landslides are evidence of high future hazard. Large areas without mapped landslides may indicate little potential for hazard, but some such areas may have unmapped landslides or future mass movement potential. The characteristics of failed slopes may help in assessing the factors related to instability. A hazard map, which distinguishes failed areas and areas with similar characteristics from areas with no failures which have few characteristics in common with failed areas, provide a basis for proactive planning.

The stability of slopes depends on many factors (Table 1.1; Cooke and Doornkamp, 1990). These factors are grouped as intrinsic conditions of slope and extrinsic conditions

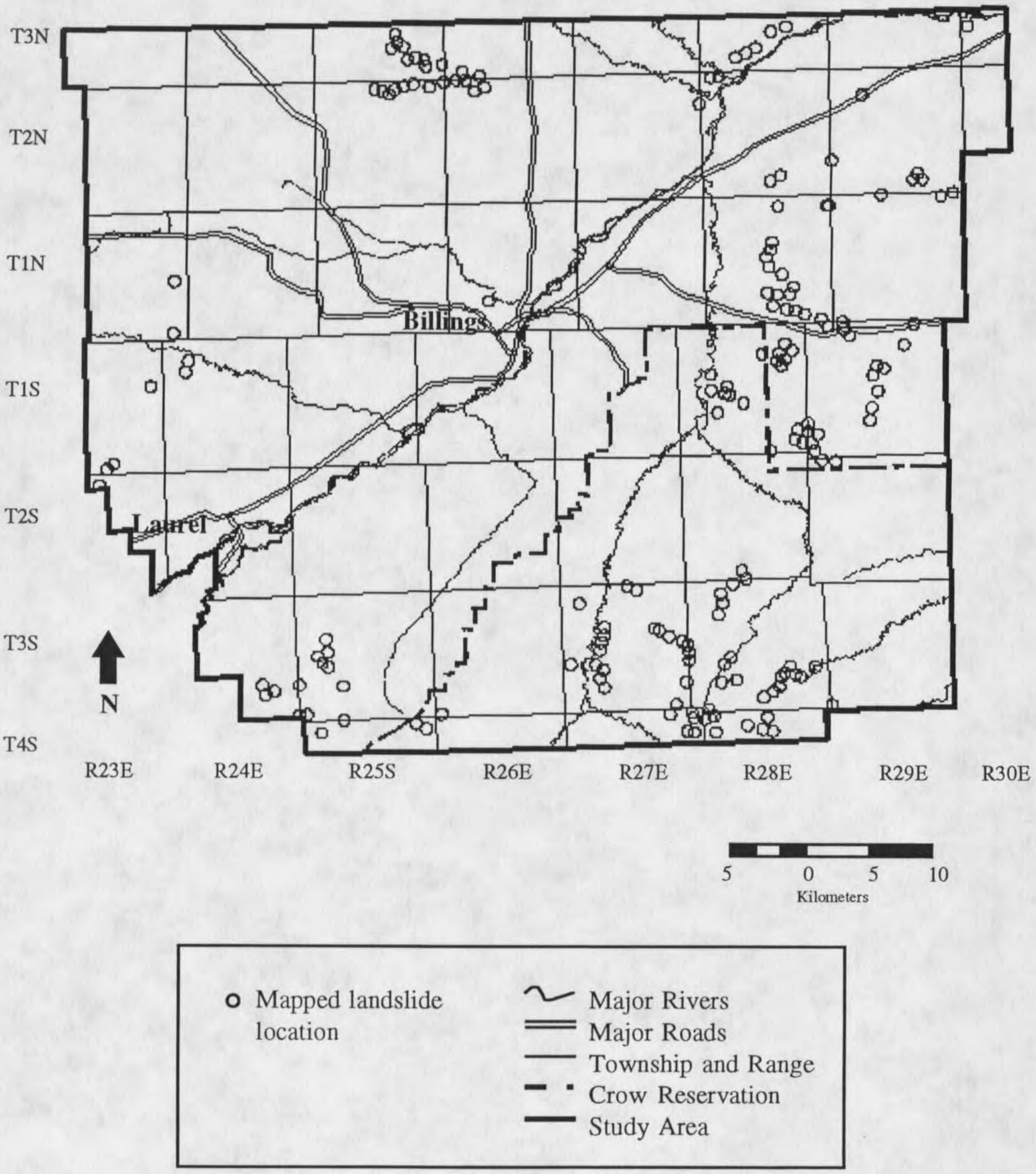


Figure 1.8. Location of mapped landslides in study area (From Wilde and others, unpublished).

acting on the slope. Extrinsic conditions are short term events which trigger slope failure. Intrinsic characteristics of topography, hydrology and material properties are long term 'causes' in slope stability. In order for a slope to fail, the intrinsic conditions have to be sufficiently weak for the extrinsic condition (a trigger event) to initiate failure. A planning map cannot predict *when* failure will occur, however, through analysis of internal conditions such a map can suggest *where* failure is likely.

Internal factors related to stability are largely related to the slope material. Cooke and Doornkamp (1990) separate material into bedrock and soil properties. Bedrock (a consolidated material) has very different physical properties than soil (an unconsolidated material). Each requires distinct characterizations. All of the mapped landslides in Yellowstone County are on Cretaceous rock units. Even though there is little distinction between the physical properties of weathered shale and soil, field analysis indicates that the depth of highly weathered shales is limited to less than ½ m on sloped areas. Because of the thin weathered depth the study is limited to an analysis of rock slope stability.

Accurate analysis of rock slope stability is a complex problem because of the many interacting factors. Factors include slope gradient, seismicity, vegetative cover, precipitation, and various hydrologic, topographic, and material properties (Table 1.2). External (triggering) and hydrologic properties have minimal representation in published slope stability studies. Typically, material properties of rock type or strength have been used. Discontinuities were recognized as important by Selby (1980) but have been ignored until recent work by Alexander and Formichi (1993).

TABLE 1.1. FACTORS RELATED TO LARGE-SCALE INSTABILITY
(After Cooke and Doornkamp, 1990, Table 5.5, p. 120-121).

Short Term 'Triggers' **Extrinsic Conditions**	**Earthquake**	Tremor Frequency
	Human Activity	Excavation Location on Slope
		Excavation Depth
		Lowering of Reservoir
		Reservoir
		Drainage Diversion
		Loading of Upper Valley Side
		Removal of Vegetation
	Climate	Rainstorm Event
		Snowmelt Event
Long Term 'Causes' **Intrinsic Conditions**	**Topography**	Valley Depth
		Slope Gradient
		Cliffs
		Valley Height Differences
	Hydrology	Drainage Density
		River Gradient
		Slope Undercutting
		Concentrated Seepage Flow
		Standing Water
		Recent Incision
		Pore Water Pressure
	Material Properties (Rock)	Jointing Density
		Jointing Openings
		Joint Orientation
		Joint Dip Relative to Slope
		Joint Gouge
		Strong Beds Over Weak Beds
		Degree of Weathering
		Compressive Strength
		Coherence
	Material Properties (Soil)	Coherent Over Incoherent Beds
		Depth
		Shear Strength
		Plastic Limit
		Liquid Limit

TABLE 1.2. CHRONOLOGICAL EVOLUTION OF FACTORS USED TO MODEL ROCK SLOPE STABILITY. COMPARISON OF INTRINSIC AND EXTRINSIC FACTORS USED IN 13 REGIONAL SLOPE STABILITY MODELS.

			a	b	c	d	e	f	g	h	I	j	k	l	m
INTRINSIC	Topographic	Slope Aspect	✓	✓	✓	✓				✓	✓	✓	✓		
		Slope Gradient	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Slope Shape						✓		✓	✓		✓	✓	
		Elevation						✓		✓			✓	✓	
	Hydrologic	Drainage Density		✓	✓										✓
		River Gradient		✓											
		Pore Pressure					✓		✓						
		Seepage Flow	✓	✓				✓							
	Material	Jointing Density	✓									✓			✓
		Jointing Openings	✓												
		Joint Orientation	✓						✓				✓		✓
		Joint Dip	✓						✓				✓		✓
		Joint Fill	✓												
		Strong Over Weak Beds													
		Degree of Weathering	✓						✓						
		Material Strength	✓				✓				✓				
		Material Type		✓	✓	✓	✓		✓	✓		✓	✓		✓
EXTRINSIC		Seismicity				✓		✓						✓	
		Precipitation					✓								
		Vegetation Cover				✓				✓			✓	✓	
		Previous Landslides		✓			✓			✓	✓		✓		✓
			a	b	c	d	e	f	g	h	I	j	k	l	m

a. Alexander and Formichi, 1993
b. Carrara et al., 1991
c. Gao and Lo, 1991
d. Gupta and Joshi, 1990
e. Jibson and Keefer, 1989
f. Bernknoff et al., 1988
g. Cruden and Eaton, 1987
h. Duncan, Ward, and Anderson, 1987
I. Wieczorek, Wilson, and Harp, 1985
j. Carrara, 1983
k. Lessing, Messina, and Fonner, 1983
l. Churchill, 1982
m. Selby, 1980

Hydrologic properties are sparsely represented in past stability models. Selby (1980) argued that the importance of hydrologic factors is overshadowed by other factors related to rock slope stability because the hydrologic factor which most directly interacts with slope (outflow of groundwater) is the least significant independent slope strength factor (Table 1.3). Hydrologic factors of slope stability are usually analyzed for site analysis. Because this study is regional in nature and hydrologic variables usually vary temporally, these factors are not included in this analysis.

All previous models used slope gradient and many also used slope aspect or other topographic factors. Slope gradient is invariably used because of its theoretical importance. Without a gradient, there would be no potential for movement. The downslope component of the force of gravity parallel to the surface partly determines the state of slope stability (Wadge, 1988). Occurrence of mass movement on various slope gradients indicate that other factors resist more or less successfully the force of gravity along a slope. Slope aspect is often significant, presumably because of the effect of aspect on evapotranspiration, and the water balance of the slope.

The mechanical properties of the slope material are also integral to stability. Discontinuities such as joints, faults, fractures and bedding planes are important to stability since they are locations where movement has occurred or will likely occur because of lower resistance than surrounding areas with out discontinuities. The nature of such discontinuities within the material (spacing, orientation, width, and continuity) is the most significant factor in rock slope stability (Table 1.3; Selby, 1980).

TABLE 1.3. ROCK MASS STRENGTH CLASSIFICATION. SLOPE STRENGTH r VALUES FOR 7 VARIABLES OF HIGH TO LOW SLOPE STRENGTHS WHERE SUM r < 26 IS RATED VERY WEAK, 50≤ SUM r > 26 IS RATED WEAK, 70 ≤ SUM > 50 IS RATED MODERATE, 90 ≤ SUM > 70 IS RATED STRONG, AND 100≤ SUM > 90 IS RATED VERY STRONG (AFTER SELBY, 1980, TABLE 6, p.44-45).

RELATIVE STRENGTH **VARIABLE**	**HIGH**	**MODERATELY HIGH**	**MODERATE**	**MODERATELY LOW**	**LOW**
INTACT ROCK STRENGTH	>200 MPa r:20	100-200 MPa r:18	50-100 MPa r:14	25-50 MPa r:10	25-1 MPa r:5
WEATHERING	none r:10	slight r:9	moderate r:7	high r:5	complete r:3
SPACING OF DISCONTINUITY	> 3 m r:30	3-1 m r:28	1-0.3 m r:21	300-50 mm r:15	< 50 mm r:5
DISCONTINUITY ORIENTATION	steep dips into slope cross joints r:20	moderate dips into slope r:18	horizontal dips, or nearly vertical r:14	moderate dips out of slope r:9	steep dips out of slope r:8
WIDTH OF DISCONTINUITY	< 0.1 mm r:7	0.1 - 1 mm r:6	1 - 5 mm r:5	5 - 20 mm r:4	> 20 mm r:2
EXTENT OF DISCONTINUITY	none continuous r:7	few continuous r:6	continuous no infill r:5	continuous thin infill r:4	continuous thick infill r:1
OUTFLOW OF GROUNDWATER	none r:6	trace r:5	slight r:4	moderate r:3	great r:1

In sedimentary rocks bedding planes are the primary discontinuity. "The bedding planes are almost invariably surfaces of minimum shearing resistance" (Terzaghi, 1962, p.258). Slope aspect may be a good predictor because aspect accounts for discontinuity orientation. For example a southern aspect may correlate with failure when mechanism for failure is actually a bedding discontinuity orientation that dips to the south often at a lower angle than topographic slope. Bedding planes will be the type of discontinuity analyzed in this study.

The relative orientation of bedding planes with respect to the topographic aspect is an important slope stability factor (Cruden, 1988). Where the topographic aspect is in the same direction as the orientation of bedding dip (Fig. 1.9A), slopes are termed *cataclinal*; where the topographic aspect is in the opposite direction as bedding dip, slopes are termed *anaclinal*. Slopes where the topographic aspect and the orientation of bedding dip are not parallel are termed *plagioclinal*; except for *orthoclinal* slopes, where the topographic aspect is nearly perpendicular to the orientation of bedding dip. Cataclinal slopes (Fig. 1.9B) are further subdivided into underdip slopes (where the surface gradient is less than the dip of bedding), and overdip slopes (where the gradient is equal to or greater than dip) (Briggs et. al., 1975).

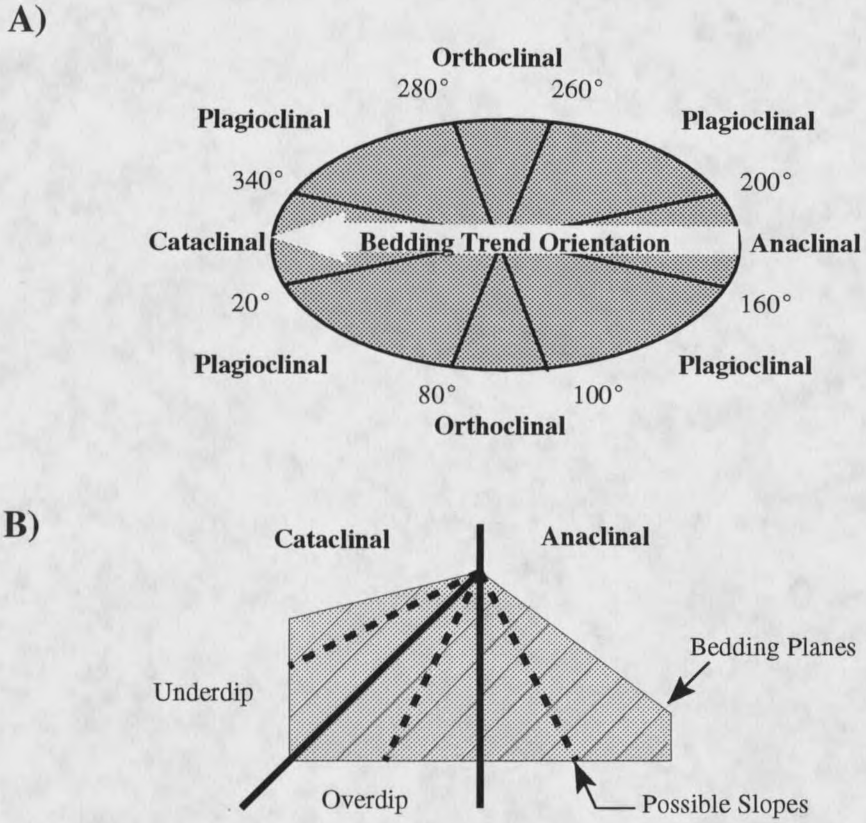


Figure 1.9. Classification of rock slopes (After Cruden, 1985, p.529). A) Topographic aspect with respect to bedding trend orientation. B) Topographic gradient with respect to bedding trend dip.

Cruden and Eaton (1987) observed that slope failures in Kanaskis Country, Alberta, Canada occur dominantly on cataclinal overdip slopes (Fig. 1.10) even though they make up less than 10% of the total area examined. A useful ratio can be created by dividing the percent of all slope failures in a particular class by the percentage of the study area that is in this class. This ratio will be referred to as the "failure per area" or FPA ratio throughout the remainder of this paper. A large FPA ratio indicates that slope failure is unusually common in the indicated slope type. A small FPA ratio indicates that slope failure is rare in the slope type class. Note that cataclinal overdip slopes have a very high FPA ratio (4.4) and are prone to slope failure (Fig. 1.10). Cataclinal underdip slopes, however, are unlikely to fail with a low FPA ratio of 0.3. In order to predict where rock slopes will fail cataclinal overdip slopes locations appear critical. For a gently deformed sedimentary terrain such as southern Yellowstone County, GIS is an appropriate tool to relate the factors (topography, lithology and discontinuities) to mapped and potential slope failures (Fig. 1.11).

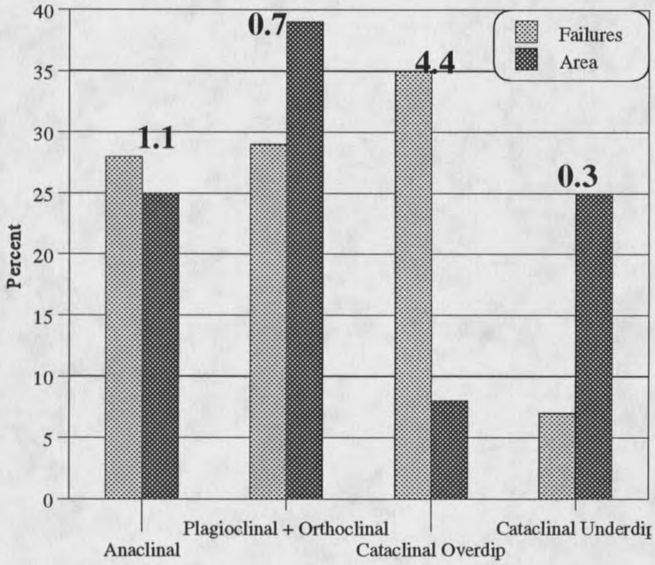


Figure 1.10. Distribution of slope failures for slope types in Kanaskis Country, Alberta, Canada. Failure/Area ratios shown (After Cruden and Eaton, 1987, Fig. 8 + 9, p.419).

A discontinuity factor which includes slope and material properties is expected to improve the prediction of slope failure locations. Slope type combined with dip should be highly correlated to slope instability (i.e. cataclinal overdip slopes most unstable and cataclinal underdip slopes most stable). Assuming slope gradient accounts for 60% of the total distinction between slope instability and slope stability then Selby's data suggests that 60% of the remaining 40% (24% of total) should be accounted for by discontinuities

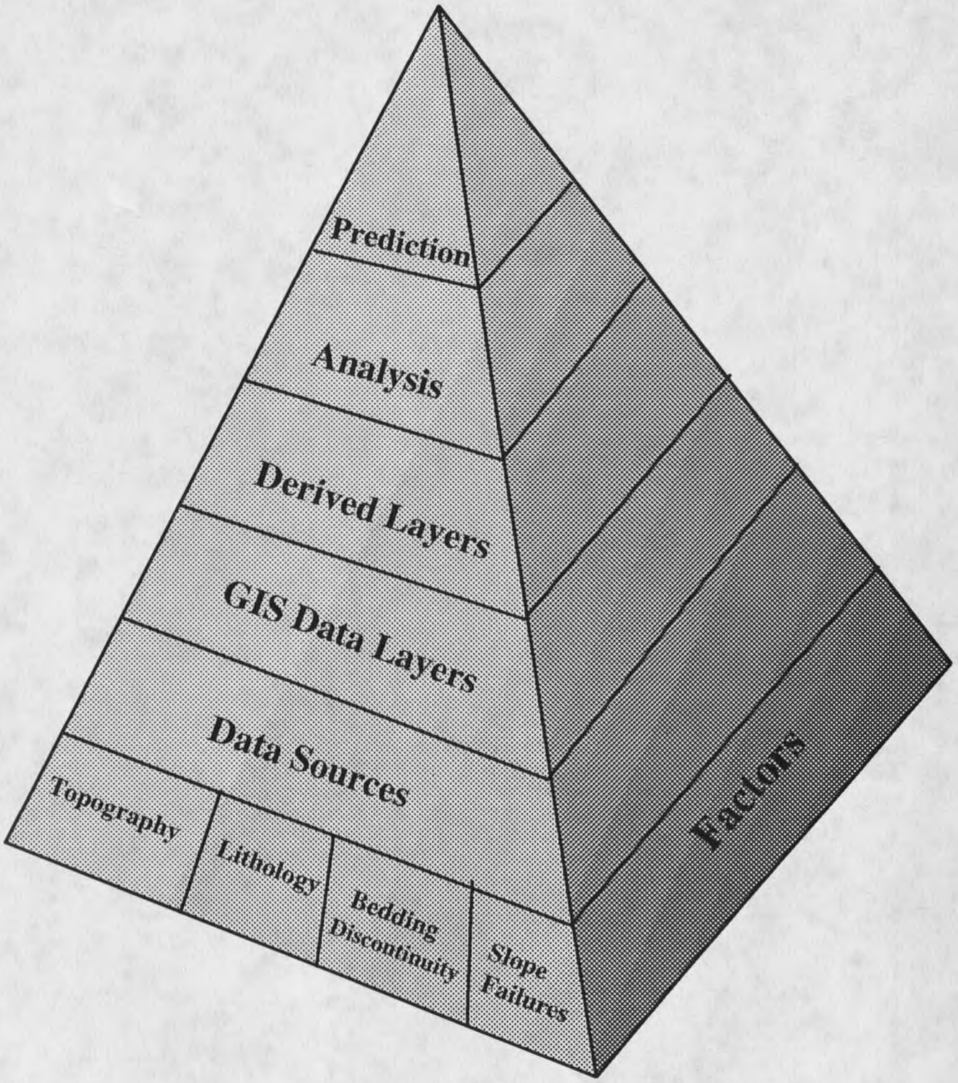


Figure 1.11. Factors for GIS stability model. Topography, lithology, bedding discontinuities and existing slope failures are foundational to this rock slope stability analysis.

(Table 1.3). The hypothesis is that slope type will account for at least half of the discontinuity effect or 12% of the total distinction between stable and unstable slopes. After observing a correlation between mapped landslide location and the mapped geologic contacts an *a posteriori* hypothesis is that the distance to a unit contact will also be significant in predicting unstable slopes.

CHAPTER 2

METHODS

The areas of potential slope failure are identified using GIS to relate the factors of slope, lithology, and discontinuities to mapped landslides. ARC/INFO is the best GIS package because of its capability to do the analysis and its availability at both the Montana State University Geographic Information and Analysis Center and the Yellowstone County Planning Department.

The GRID module in ARC/INFO is particularly suited for the analysis of continuously varying spatial data (e.g. topographic and bedding discontinuity) (ESRI, 1991). Cell operations are simpler both computationally and conceptually than polygon operations for analyzing multiple data sets (Bonham-Carter, 1994). Because the source topographic data is a 30 meter grid, no increased (finer) resolution can be gained from using a polygon model. Topography, lithology, discontinuities and mapped landslide ARC/INFO layers (Fig. 2.1) are built from the best available data sources.

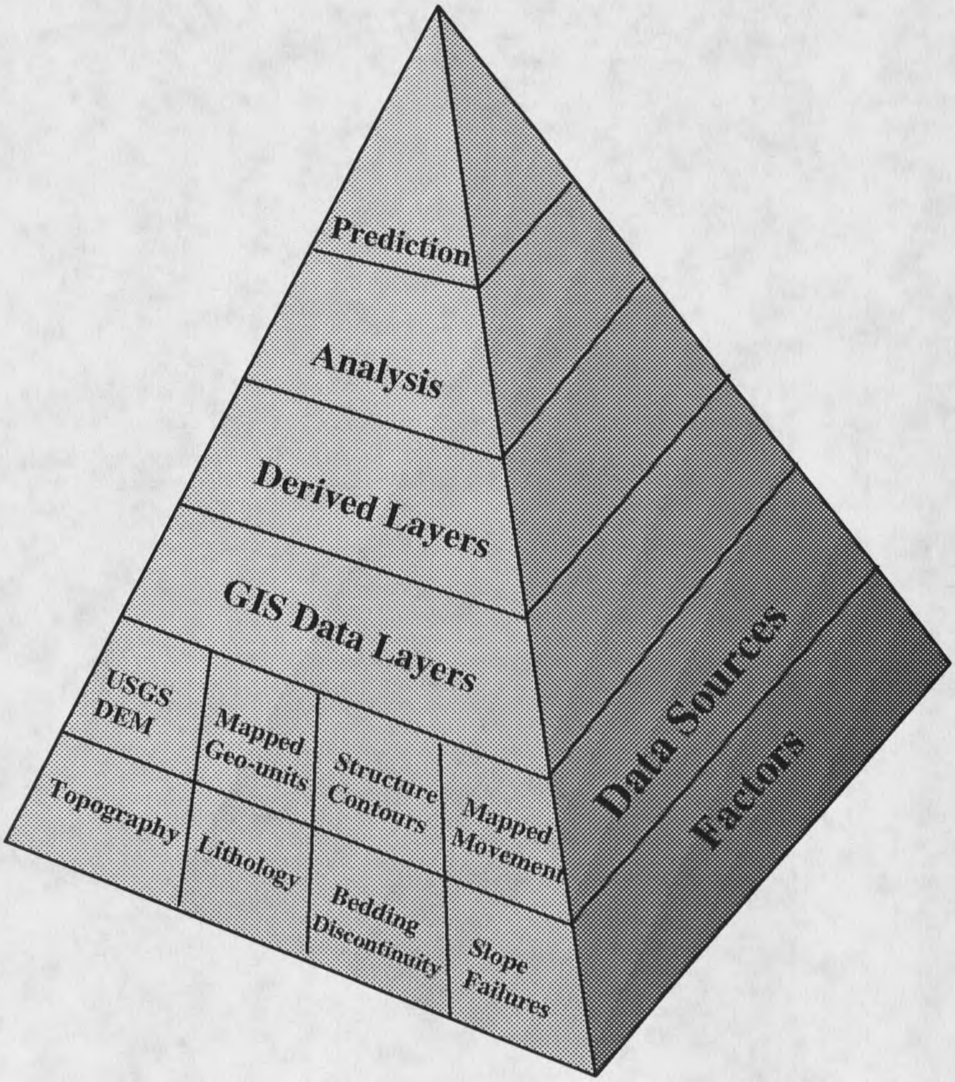


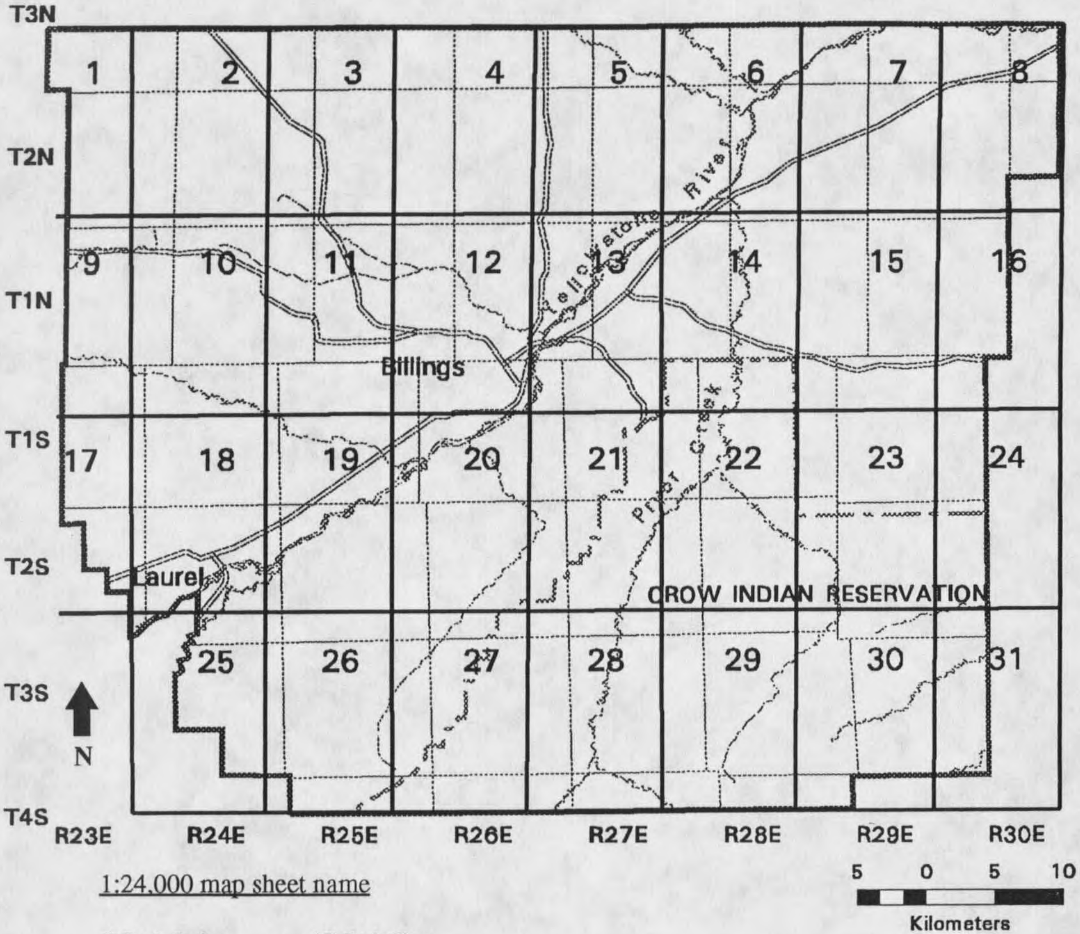
Figure 2.1. Data processing for stability analysis. Digital data (DEM) and paper maps (geologic units, structural contours and mapped movements) are the data sources used to represent the stability factors.

Data Layers

Digital Elevation Model

A Digital Elevation Model (DEM) is one type of electronically structured topographic data. The United States Geological Survey (USGS) distributes 30m DEMs that correspond to USGS 7.5-minute (1:24,000) map series. DEMs are prepared by the USGS from elevation contours or digitization of stereo models of air photographs. A DEM consists of elevation points 30 meters apart both row-wise and column-wise referenced to the Universal Transverse Mercator (UTM) coordinate system (North American Datum of 1927). The study area (Fig. 2.2) is limited by the availability of the 30m DEMs within Yellowstone County (Elassal and Caruso, 1984).

The accuracy of the DEM is based on the accuracy of the 7.5-minute contour map series, which follows the National Map Accuracy Standards. Less than 10% of the data points are in error by 1/20th of a map centimeter (1/50th inch) horizontally and 15 meters (50 feet) vertically at a scale of 1:24,000 (Thompson, 1974). DEMs contain the error allowed in the topographic source maps plus an additional unknown amount of error from the contour-to-DEM conversion. The conversion process assigns a single elevation value to every 30 m cell. A resulting error is that the actual high and low points of a surface are not necessarily included in a DEM with elevation points on a uniformly sampled grid. Thus the DEM is slightly smoother than the real surface.



1:24,000 map sheet name

1) Rock Spring
2) Commanche
3) Acton
4) Hickson Ranch
5) Rattlesnake Butte
6) Huntley
7) Worden
8) Nibbe
9) Molt
10) Two Pine Creek
11) Rimrock
12) Billings W
13) Billings E
14) Cottonwood Creek
15) Indian Arrow
16) Gails Coulee
17) Park City
18) Lauel
19) Mossman
20)Yeagen
21) Soda Springs NW
22) Babby Coulee
23) Woody Mountain NW
24) North Telegraph Creek
25) Stella
26) Mossmain SW
27) Stratfore
28) Vale Creek Ranch
29) Soda Springs
30) Woody Mountain
31) Woody Mountain SE

Figure 2.2. Index map of 1:24,000 DEM sheets.

The DEMs (USGS format) are converted to an ARC/INFO grid for the study area. The grid extends 0.5 kilometers beyond the study area to eliminate edge effect error within the study area. Each grid cell except edge cells has eight neighboring cells.

Roundoff error is transmitted to the grid from the DEM. Because the DEM elevation points were rounded off by the U.S. Geologic Survey to the nearest meter, artificial steps are produced in flat areas where 1 meter rise occurs over a large run. Rather than an even change of elevation along a slope, there is no change in elevation over most of the cells along the slope but at one cell the elevation jumps a meter. In steep areas where 1 meter rise occurs over a short run, each cell along a slope increases by at least 1 meter so artificial steps are not produced. Roundoff error is compounded when calculating slope gradient and aspect. Where there is artificial stepped topography the gradient over most of the cells is much less than it should be. At the steps there are narrow linear areas with a gradient much steeper than it should be.

The typical solution to this problem is to filter the elevation data by replacing each cell value with an average of it and its neighbors. Low pass filters average over a small area (e.g. 3X3 cells) and high pass filters average over a large area (e.g. 9X9 cells). A low pass filter averages everything a little but does not eliminate the stepped slopes. The high pass filter averages out the stepped slopes but also flattens out topographic peaks, ridges and valleys which are more accurately represented on the original DEM. To eliminate the artificial steps without corrupting the actual steep slopes a variable filter was needed which could average over large areas of low change in elevation without averaging large areas with high change in elevation. A customized filter was used that averaged the elevation over a varying area (Table 2.1) depending on the variation in elevation over a 9X9 cell window..

TABLE 2.1. COMPARISON OF FILTERS USED FOR SMOOTHING ELEVATIONS.

Difference in elevation (δe) over a 9X9 window	**Size of window (area) used for average**
$\delta e <= 20$ m	**9X9 (72,900 m^2)**
20 m > $\delta e <=$ 40m	**5X5 (22,500 m^2)**
40 m > $\delta e <=$ 80 m	**3X3 (8,100 m^2)**
$\delta e > 80$ m	**1X1 Not Averaged**

The variable filter produced the best smoothing of artificially stepped low angle slopes with least modification of accurately depicted high angle slopes. All of the filters raise the minimum elevation ~1m above the minimum DEM value (Table 2.2). The variable filter lowers the maximum DEM elevation 1.6m which is nearly as good as the 3X3 filter. The maximum difference between the variable filter and the original DEM (1X1) is 27m which is better than any of the fixed-size filters. The mean difference between the variable filter and the DEM is 1.5m which is comparable to the 5X5 filter. Thus, the error that the variable filter introduces is similar to that of a uniform 3X3 or 5X5 filter. The benefit of the variable filter is that the low angle steps are removed, unlike the 3X3 or 5X5 filters, and the high angle topography is preserved better than with the 9X9 filter.

The first data layer derived from the filtered elevation grid is slope aspect. Slope aspect is calculated from the elevations of the eight neighboring cells with the ARC/INFO ASPECT function. Cell center points to the north, south, east and west are 30 m away from the cell being calculated. ARC/INFO determines the resultant vector of each of the neighboring cells values where aspect is the direction of that resultant vector. The final grid consists of a compass direction (0 to 359 degrees from north) of a "60 m aspect" because it is effectively an average over 60 m.

Slope gradient is derived from the filtered elevation grid similar to slope aspect. Slope gradient (ARC/INFO SLOPE function) is the magnitude of the resultant vector. The derived grid of slope gradient has the value of effectively the "60 m slope" in each grid cell.

TABLE 2.2. COMPARISON OF FILTERED TOPOGRAPHIC DATA (FROM TABLE 2.1).

Filter	**Minimum Elevation**	**Maximum Elevation**	**Mean Elevation**	**Standard Deviation**	**Maximum difference of Abs(DEM - Filter)**	**Mean difference of Abs(DEM-Filter)**
1X1*	867.00	1518.00	1099.87	110.19	0.0	0.0
3X3	867.89	1516.89	1099.87	110.13	37.78	0.69
5X5	868.00	1516.16	1099.87	110.10	52.96	1.52
9X9	868.22	1514.52	1099.89	110.99	63.25	3.05
VF†	868.22	1516.44	1099.81	110.13	26.89	1.49

Note: All values are in meters. *1X1 indicates original cell value of source data. †VF = Variable sized filter

Material

Material data is stored in a grid where each cell has a value representing the dominant lithologic unit at that location. Lithologic information for the study area was compiled from several published geologic maps (Fig. 2.3, Hancock, 1919; Hancock, 1920; Knappen and Moulton; 1930 and Thom and others, 1935; Gosling and Pashley, 1973). The geologic source maps were digitized and pieced together into a single polygon coverage. Each polygon within the coverage represents a single mapped lithologic unit.

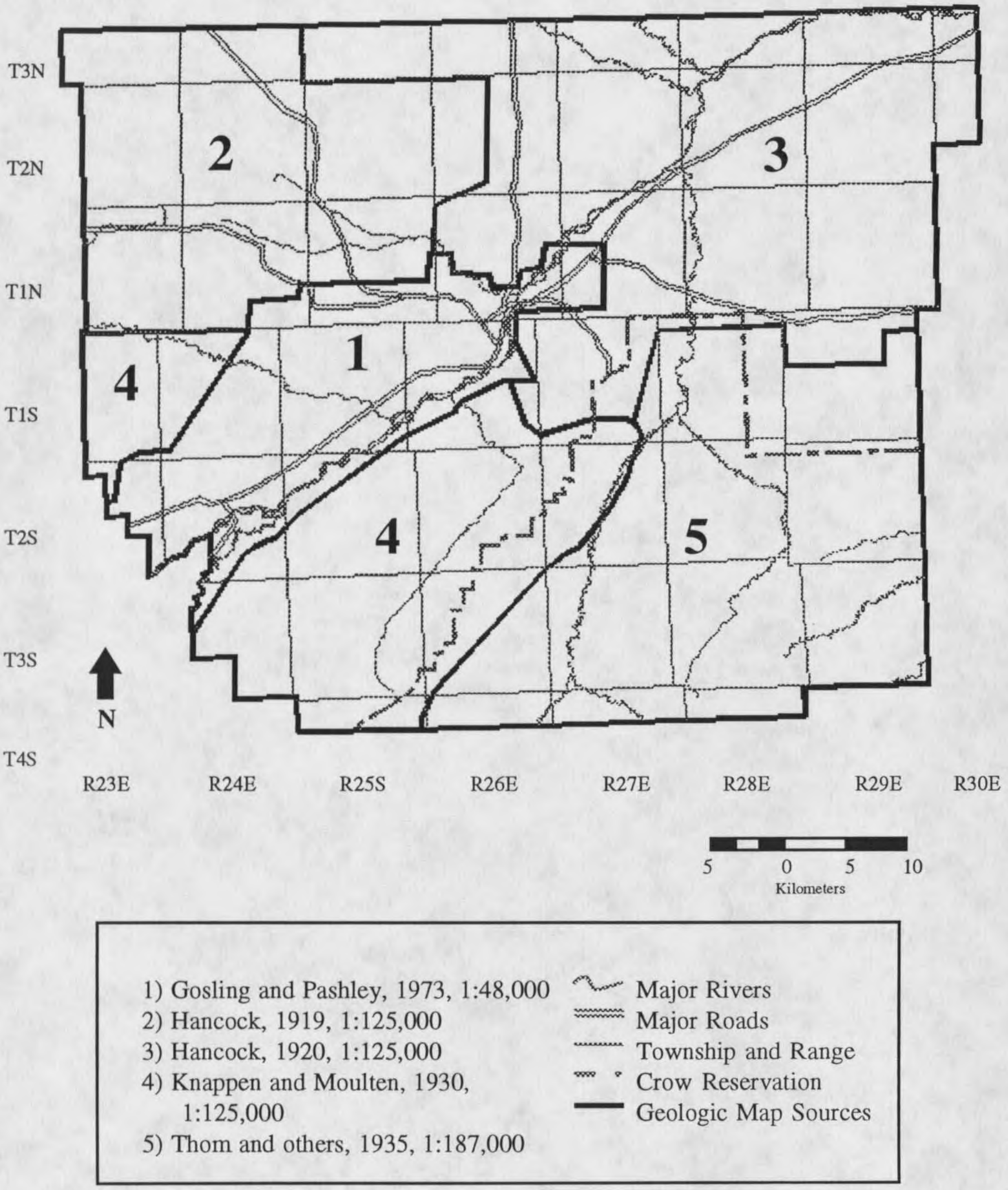


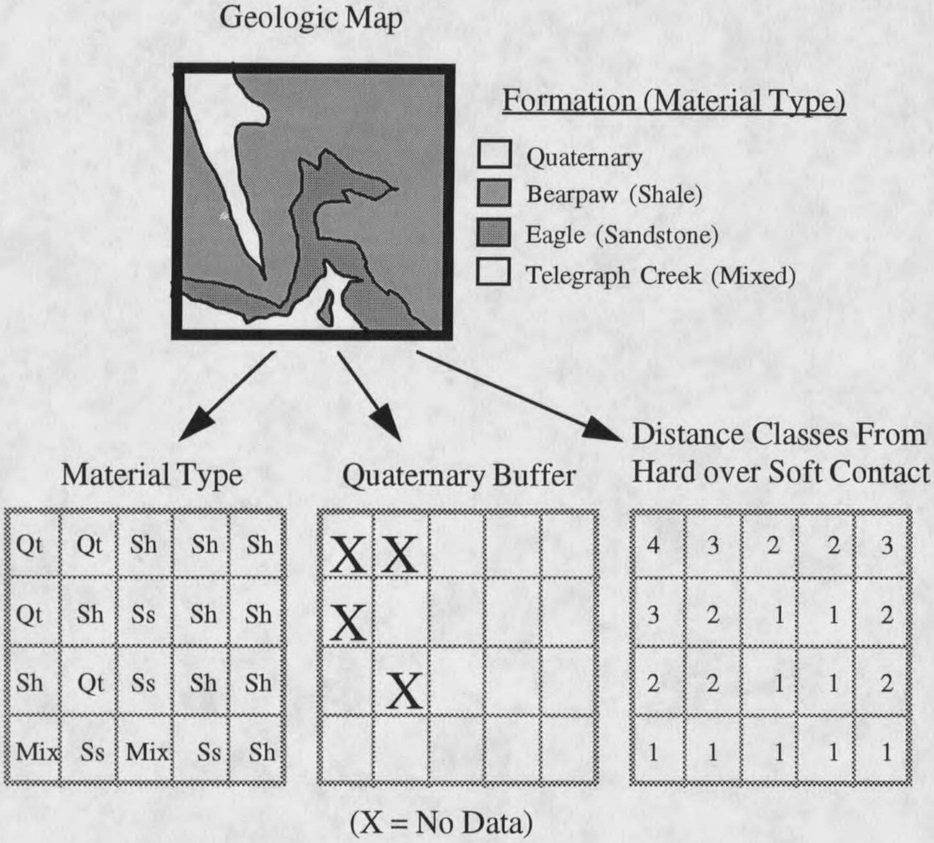
Figure 2.3. Index map of geologic sources. Publication dates and map scales are shown.

Spatial error in location varies within the polygon coverage. The greatest uncertainty is in the location of polygon boundaries representing the mapped unit boundary. Visual estimation of the map condition was made at the time of digitizing. All of the maps were folded and had an unknown amount of distortion along the folds. The amount of error due to fold distortion of the paper was determined as the distance a point on the map could move while the map corners were pulled taut and fastened. Thom and others' (1935) map for the southeast corner of the study area had severe fold creases which produce an estimated maximum ground error of 3 km in the east-west direction with a lesser amount of error in the north-south direction. Hancock's (1919) map for the north west corner of the study area was in fair condition, having an estimated maximum error of 0.2 km from distortion. The rest of the maps were in good condition (Gosling and Pashley, 1973) or very good condition (Hancock, 1920; and Knappen and Moulton, 1930) with a minimal amount of error due to map fold distortion.

Further uncertainty is inherent in the scale or resolution of the source map. The amount of uncertainty depends on the scale of the source map and digitizing error and any mapping error on the original maps. Digitizing error depends on human accuracy, the condition of the source map, and edge matching of the different source maps. The best defined source map lines (Gosling and Pashley, 1973) are mapped at the largest scale (1:48,000). A location within 0.05 cm (digitizer resolution) on a 1:48,000 scale map could vary by 24 m on the ground (one 30X30 m cell). The source map with the greatest error (Thom and others, 1935) has the smallest scale (1:187,000). A 0.05 cm digitizer error at 1:187,000 represents 94 m on the ground (three 30 m cells). The remaining three source maps of the study area (Hancock, 1919 and 1920; Knappen and Moulton, 1930) have a scale of 1:125,000. A 0.05 cm digitizing error at 1:125,000 represents 63 m (two 30 m cells) on the ground. Combined error from folds and inherent precision due to scale suggests that the total material unit boundary error ranges from little as 0.03 km, or 1 cell (Gosling and Pashley, 1973) to as much as 3 km, or 100 cells (Thom and others, 1935).

In the primary grid, each cell contains a value from digitized polygons which represents lithologic units. A reclassified materials grid was created from the lithologic units. From the reported descriptions and thicknesses the lithologic units were classified as dominantly sandstone, dominantly shale, or a mixture. Quaternary units were eliminated for each of the grids derived from lithology because Quaternary alluvium is not a consolidated lithologic unit with comparable bedding discontinuities (Fig. 2.4).

In addition to material type and the Quaternary buffer, another type of grid is created from the contacts between lithologic units (Figure 2.5). Contacts where a hard unit overlies a relatively weaker unit (h/s contacts) such as sandstone over mixed, sandstone over shale or mixed over shale, correlated visually with mapped landslides. Each grid cell was given a value relating to the distance to an h/s contact. The study area was divided into five distance classes from an h/s contact: within 125 m, greater than 125 m and within 250 m, greater than 250 m and within 500 m, greater than 500 m and within 1 km, and greater than 1 km. One hundred twenty five m is roughly an accurate location of the contact ± map condition ± digitizing error, thus 0 - 125 m indicates "on" the contact. The remaining classes represent an exponential increase in class size, conforming to the way most geologic processes behave.



Material Type

Qt	Qt	Sh	Sh	Sh
Qt	Sh	Ss	Sh	Sh
Sh	Qt	Ss	Sh	Sh
Mix	Ss	Mix	Ss	Sh

Quaternary Buffer

X	X			
X				
	X			

Distance Classes From Hard over Soft Contact

4	3	2	2	3
3	2	1	1	2
2	2	1	1	2
1	1	1	1	1

(X = No Data)

Figure 2.4. Derived Grids From Lithology. Material type is evaluated for each cell. Quaternary material are given no data values. Distances are calculated from hard over soft contacts. Note cells shown are approximately 300x300 m, actual resolution is 10 times better.

Figure 2.5. Distance of landslides to Hard over Soft contacts and Soft over Hard contacts in Yellowstone County, Montana.

Bedding Discontinuity

Rock discontinuities, such as bedding, jointing, and foliation, are usually represented by strikes and dips measured in the field. However, in this study field mapping cannot accurately represent bedding discontinuity because dip angles are very small and mapping is limited to exposed unweathered rock outcrops and there is little exposed unweathered rock. The problem of sparse dip data is not insurmountable. Dip is also characterized by structure contours. Structure contours are the elevation of a selected stratigraphic datum, either above or below sea level. Characterization of bedding discontinuities from structure contours assumes that the surface defined by the elevation contours on a stratigraphic datum within the Cretaceous is representative of the structure at the surface. The contours are inferred to be representative of surface dips because: 1) the structure deformation is uniform (outside the fault zones) from the uniform Pryor uplift to the south, 2) all of the formation and member units are continuous and conformable from the Cloverly up to the Lance (Knappen and Moulten, 1930), and 3) the original map contours appear to be inferred from surface structure (from the observed agreement of mapped strike and dips with structure contours), probably because very few wells existed at the time of mapping in the 1930's. These structure contours can be incorporated into the GIS rock slope stability analysis. Field mapping could then be focused on specific areas shown to be of concern.

Structure contours are published on the USGS geologic maps for the southern three-quarters of the study area. The contour data comes from the four geologic maps represented in Figure 2.3 excluding the map of Gosling and Pashley (1973). Contours in the south are elevations of the top of the Cloverly Formation. Contours in the north are elevations of the base of the Eagle Sandstone. Where the Eagle Sandstone and Cloverly Formations outcrop (north and south of study area respectively) structure contours are not drawn.

Oil and gas well log data provides some additional information in areas not covered by contours. The well locations are plotted on a 1:100,000 scale map from the north-south and east-west distances from section lines given on the well logs. The elevation at the top of the Eagle Sandstone was taken from the log at each location.

Both the contour surfaces and the well elevations were adjusted to the top of the Eagle Sandstone (Fig. 2.6). This datum was used because the shale-sand transition at the top of the top of the Eagle Sandstone (the prominent Rimrock sandstone as seen in Billings) is easier to identify in the well logs than the base of the Eagle Sandstone, which grades from sand to sandy shale layers. Contours at the base of the Eagle are raised 64 m to account for the thickness of the formation (Knappen and Moulten, 1930). Contours at the top of the Cloverly are raised a total of 836 m, 772 m up to the base of the Eagle plus 64 m to the top of the Eagle (Knappen and Moulton, 1930).

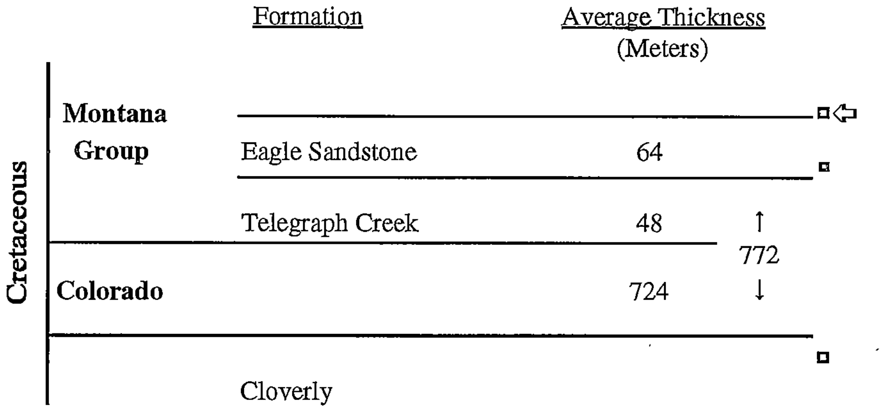


Figure 2.6. Elevation data for discontinuity surface. Note: □ elevation data locations, ⇦ synthesis location (From Knappen and Moulten, 1930, p. 8-9).

A grid was created by fitting a surface to the elevation points from well picks and structure contours on the top of the Eagle Sandstone. None of the interpolation methods in ARC/INFO (inverse weighted distance, spline, krig, or polynomial surface fit) were able to satisfactorily create a surface from points along the digitized elevation contours. The high concentration of points on the contours had to be decreased and additional values interpolated by hand between contours where contours were far apart, so that the final elevation points were approximately equally spaced (Figure 2.7) rather than grouped along contour lines (Eklundh and Martensson, 1995). Because the typical distance between data points is 1 km a spline interpolation is slightly more accurate than kriging (Heine, 1986). A structure elevation grid was created with a spline model within ARC/INFO.

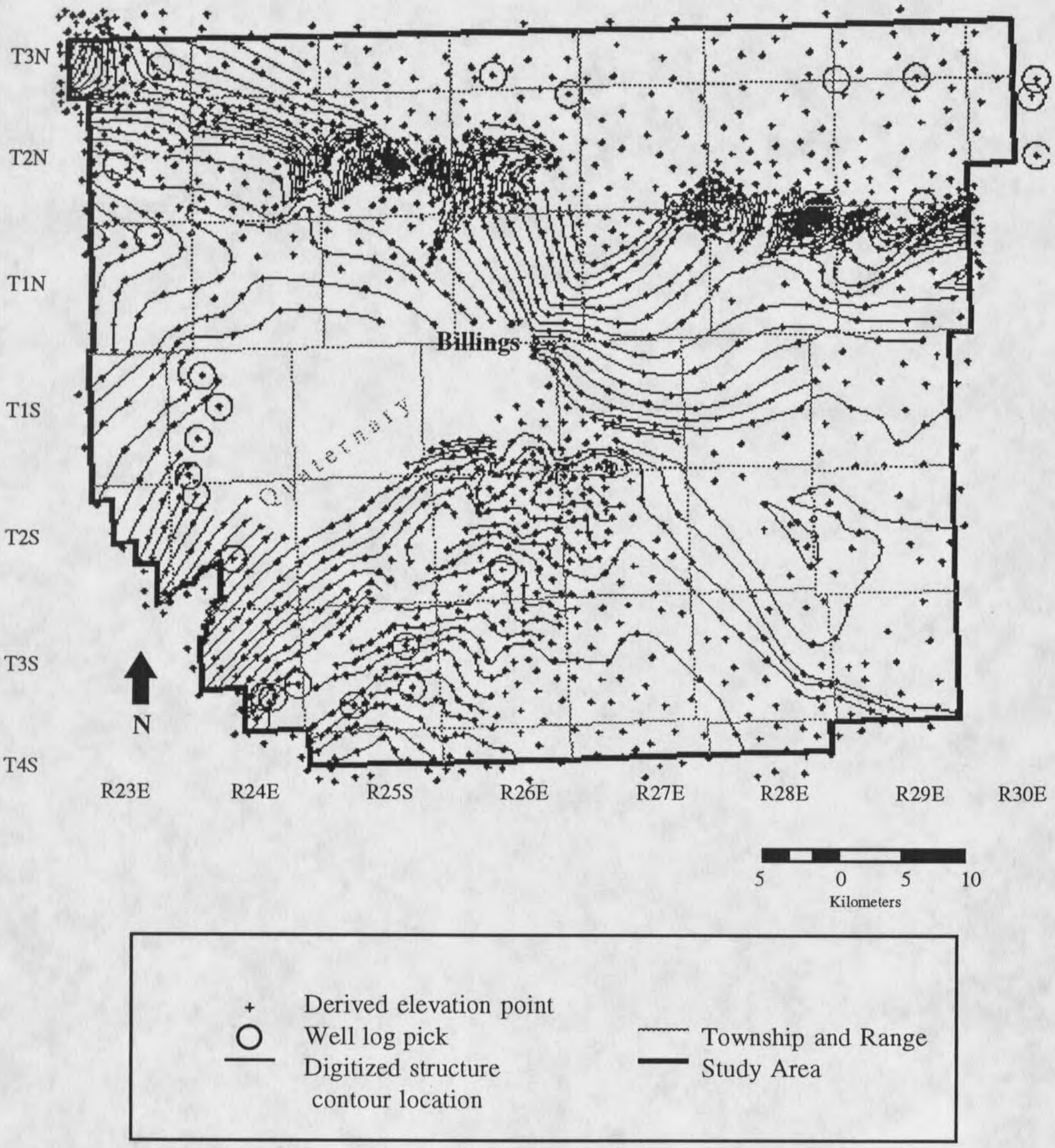


Figure 2.7. Structural elevation data points. Even spacing of data points along and between contours are used to create a non-linear biased set of data points to generate a surface. Points are derived from digitized structural contours with values adjusted to the top of the Eagle Sandstone Formation.

Areas in the Lake Basin and Fromberg fault zones have a high amount of local variation in the structural trend. The resolution of fault locations and amount of deformation is not sufficient to accurately represent the bedding discontinuity surface at the faults, thus a one kilometer (the typical distance between data points) buffer was created around each mapped fault to exclude fault regions from further structure analysis (Fig. 2.8). This excluded approximately 13% of the area. In the final discontinuity grid, each cell contains the elevation of the top of the Eagle Sandstone except for the fault buffered areas.

Mapped Landslides

The locations of mapped landslides (Wilde and others, unpublished) in the study area were digitized into a point coverage. A point coverage was used because most of the landslides are too small to be accurately represented by polygon areas (Fig. 2.9A). Although some landslides are as large as 0.5 km^2 they are digitized as points (Fig. 2.9B) because of the 1:500,000 source map scale. The small source map scale suggests a position error of ±250 m (0.05 cm x 500,000), equivalent to an area covered by eight 30 m cells. As a result, the actual point could be in one of 64 possible cells, thus an area representation of landslide location is inappropriate. The point coverage was converted to a 30 m cell grid (Fig. 2.9C). Each cell is assigned a value indicating the presence or absence of a mapped landslide. Because a landslide is represented by a single point, cells containing part of a large landslide may have a no failure value (Fig. 2.10). A cell containing a failure value will not necessarily represent either the steepest or flattest area of the landslide.