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Structural control of the morphometry of open rock basins, Kananaskis region, Canadian Rocky Mountains

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Abstract

The morphometry of chutes (couloirs), rock funnels, and open cirques are related to the structure of dissected rock masses in the Kananaskis region of the Canadian Rocky Mountains. Data for ten morphometric variables were derived from digital elevation models of 56 open rock basins. The basins were classified structurally according to the relative orientations of bedding planes and the rock slopes. A hypothesis of no differences in morphometry among structural classes is rejected from the results of nonparametric analysis of variance and paired comparisons of rank scores. Basins on dip and overdip slopes have a distinct size, and those on anaclinal slopes have a distinct width and shape. Variation in morphometry from low compactness and area/relief (chutes) to high compactness and low area/relief (funnels) to high compactness and area/relief (open cirques) corresponds to a change in dominant structure from orthoclinal to dip–overdip to underdip to anaclinal. The dip of bedding planes relative to the slope of rockwalls controls the mode of initial displacement of joint blocks and, thereby, the spatial distribution of the retreat of rockwalls. The angle between the rock slope and the strike of dipping strata determines whether beds of differing stability form chutes and buttresses (orthoclinal slopes), or extend across rockwalls (cataclinal and anaclinal slopes) and retreat at similar rates to form funnels and open cirques. The optimal structure for large compact rock basins is anaclinal, and the least favourable is cataclinal dip–overdip slopes. Topoclimate and other geologic structures may account for variance in morphometry not explained by differences among structural classes. © 1998 Elsevier Science B.V.

Keywords: mountains; rock slopes; open rock basin morphometry; geologic structure

1. Introduction

The geomorphic significance of geologic structure is implicit in studies of steep mountain slopes (Rapp, 1960; Luckman, 1988). These slopes, however, have received relatively little attention compared to the preoccupation of geomorphologists with coarse debris landforms in alpine environments (Klimaszewski, 1971; Gerber and Scheidegger, 1973). This disparity may reflect the impracticality of field experiments on precipitous slopes and the more immediate link between talus slopes and contemporary processes. Even though geologic control on the form of rock slopes may be intuitive, and obvious from

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cursory observation, rigorous explanation of this control is more elusive. Some control is direct, for example, planar slopes on bedding planes. Otherwise, it involves the interaction of structure, process, and form.

Current understanding of the development of steep rock slopes is based largely on the work of geomorphologists (e.g. Gerber and Scheidegger, 1973; Selby, 1982) and built on a foundation of rock mechanics (e.g. Terzaghi, 1962; Hoek and Bray, 1981). The relevant rock mechanics and geological factors depend on the nature and magnitude of the geomorphic process. Rock control in geomorphology can be subdivided into resistance to (1) weathering processes, (2) detachment of joint blocks from a rock mass, and (3) higher-magnitude deep-seated failures, where residual stress is an important consideration. This paper examines the morphometry of open rock basins

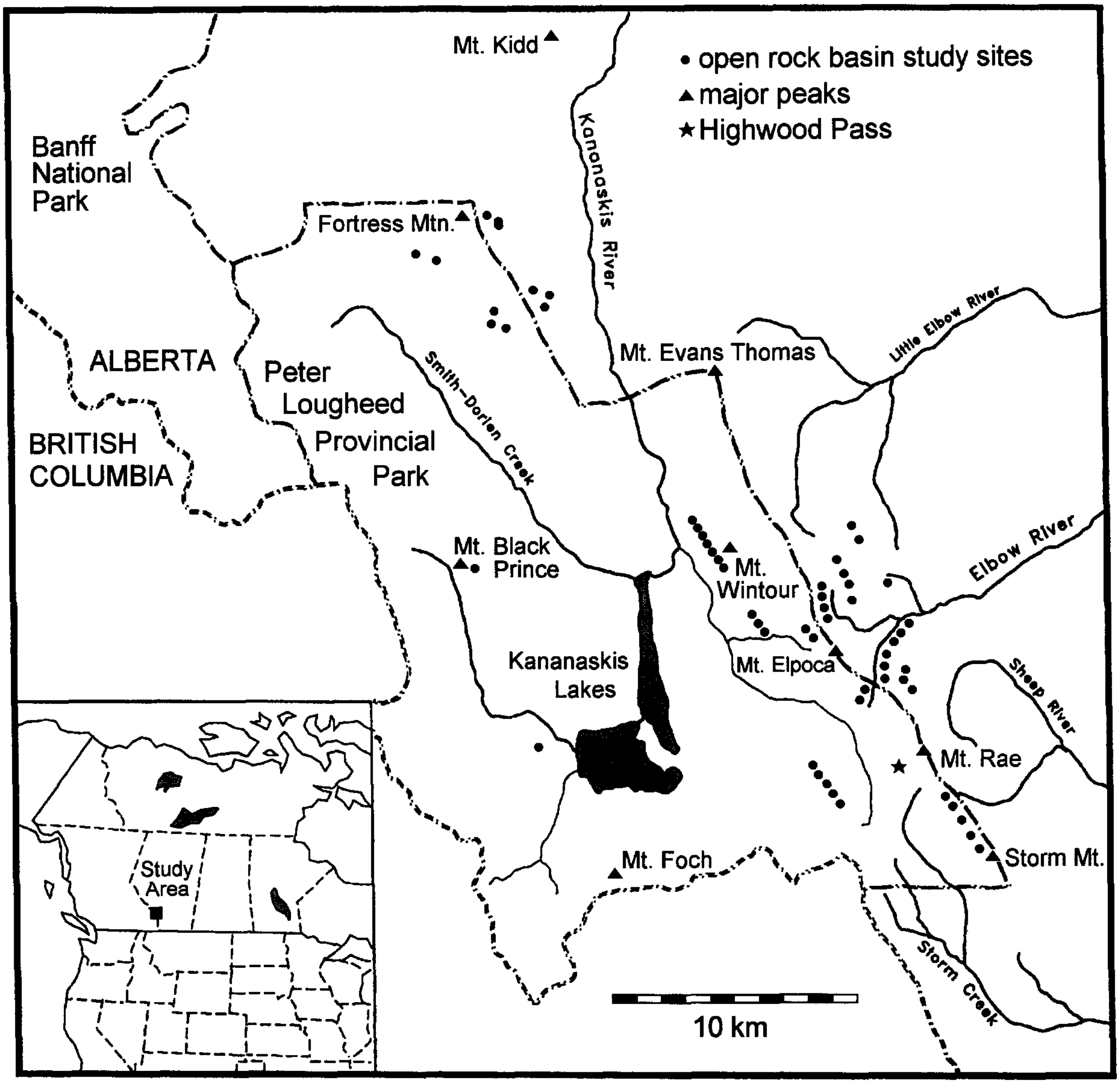

Fig. 1. The Kananaskis study area and open rock basin study sites.

formed by the mass wasting of joint blocks from rockwalls in a high mountain landscape, the Kananaskis region of the southern Canadian Rocky Mountains (Fig. 1). The controlling structural features are bedding planes and joints. The important structural parameters are the dip and strike of discontinuities relative to the rock face.

Without reference to process, morphometric studies are of limited value (Thorn, 1988). Therefore, a primary objective of this study is to relate the morphometry and structure of open rock basins to the processes that remove rock blocks from cliff faces. Rockfall is the dominant geomorphic process on mountain rockwalls, according to field observation (Gardner et al., 1983; Luckman, 1988) and as implied in models of the cliff–talus geomorphic system (Statham, 1976; Olyphant, 1983; Whalley, 1984). Blocks of rock move exclusively by falling only when unsupported. Other processes usually trigger rockfalls by projecting the blocks away from confining support. The literature on rock mechanics makes an explicit distinction between rockfall and the preceding release of rock blocks by sliding or toppling along or from joints and bedding planes (Hoek and Bray, 1981). Geomorphologists (Rapp, 1960) classify rockfall as primary or secondary, where the later requires the initial impact of snow avalanches, falling rock, or water.

2. Conceptual framework

The landforms examined here are chutes (couloirs), rock funnels, and open cirques formed by differential mass wasting of the rockwalls that bound major ridges and peaks. They are an assemblage of steep rock slopes, with gradients exceeding the angle of repose of coarse angular clasts (Carson, 1977), and lesser slopes where rock debris may be stored temporarily. Collectively these landforms are called open rock basins (Sauchyn and Gardner, 1983). They are distinct from glacial cirques; coarse sediment is transferred from open rock basins, usually to a subjacent talus cone. Various scales and morphologies of rock basin are integrated or nested spatially and functionally within the alpine cliff–talus geomorphic system. The size, distribution, and shape reflect variations in the strength of rock masses. The juxtaposition of large talus slopes and open rock basins, and estimated rates of periglacial weathering and rockfall (Gray, 1972; Soderman, 1980; Olyphant, 1983), suggest high spatial variability in the denudation of mountain rockwalls. Once weathering along fractures eliminates cohesion between rock blocks, the stability of rockwalls is governed by properties of the fractures: roughness, fill, width, frequency, and orientation (Selby, 1982). Although angles of sliding friction of the carbonate rocks in the study area range from 21° to 41°, they are usually less than 30° (Cruden and Hu, 1988). Therefore, the orientation of penetrative discontinuities relative to the gradients of rockwalls is a major control on the stability and differential mass wasting of rock masses.

Sauchyn and Gardner (1983) demonstrated a link between the morphometry and aspect of the rock basins examined here. However, structure and topoclimate vary consistently with aspect. Subsequent research by Cruden (1988) on the structural fabric of the Canadian Rockies, and its relationship to catastrophic mass wasting, provides a conceptual framework for a systematic analysis of structural control on the morphometry of open rock basins. The classification of rock mass structure is based on the relative dip and strike of penetrative discontinuities, such as bedding or schistosity (Fig. 2). Dip slopes dip in the direction of the discontinuity and scarp (or reverse) slopes face in the opposite direction. Dip

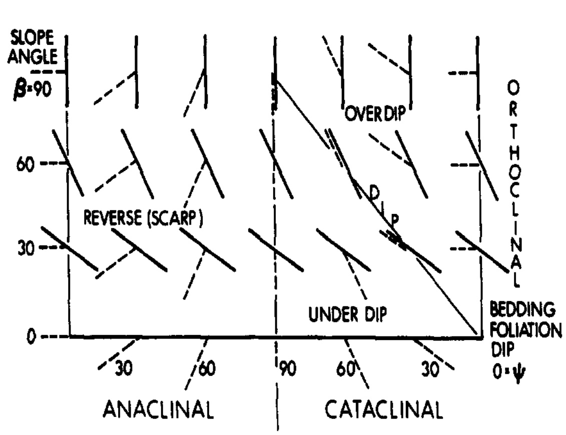

Fig. 2. A classification of rock slopes in strike valleys by the orientation of the dominant penetrative discontinuity (from Cruden, 1988).

slopes may be subdivided into overdip and underdip slopes which are steeper and less steep, respectively, than the dip of the discontinuity. Some ambiguities occur in this terminology; to avoid them, terms originally introduced by Powell (1875) can be used. On cataclinal slopes, the penetrative discontinuity dips in the same direction as the slope; on anaclinal slopes, the penetrative discontinuity dips in the direction opposite to the slope; on orthoclinal slopes, the azimuth of the dip direction is perpendicular to the azimuth of the slope direction. A similar French terminology is described in Foucault and Raoult (1984).

The influence of the relative strike of discontinuities is most apparent on orthoclinal slopes, where chutes occupy recessive beds and are bounded by more resistant strata. The chutes assume the orientation (dip) of the bedding, oblique to the rockwall, approaching verticality in steeply dipping beds, as illustrated in Fig. 3. On cataclinal slopes, rock faces conform to bedding planes (Fig. 4), and rock debris moves readily over straight steep sections of rockwall underlain by resistant strata. The strike of bedding planes also has direct morphological implications on anaclinal slopes (Fig. 5), which typically have a stepped profile. Rock debris and snow accumulate on benches and reverse slopes formed in resistant beds.

Whereas the relative strike determines the exposure of resistant and recessive beds across rockwalls, the relative dip of discontinuities determines the mechanism by which rock blocks are released, as illustrated in Fig. 6 (after Cruden, 1988). The threshold for mass wasting assumes a basic friction angle of about 30°. On slopes below this limit, gravitational shear stress alone is insufficient to move weathered rock along bedding planes and kathetal joints (perpendicular to the bedding). Buckling is not an important process in the Paleozoic limestone and dolomite, because these strata have widely spaced joints, thick beds and high compressive strengths and, thus, underlie high vertical cliffs.

Table 1, derived from Figs. 2 and 6, identifies the process(es) that release joint blocks from the rockwalls in each structural class. The dominant processes are sliding and toppling from bedding planes and kathetal joints. Where these modes of movement are inhibited by low dip and slope angles, they can occur only when assisted by external forces: the impact of runoff, snow avalanches and rockfalls, or the pressure of water or ice in fractures. From the mechanisms of rock block release and relative orien-

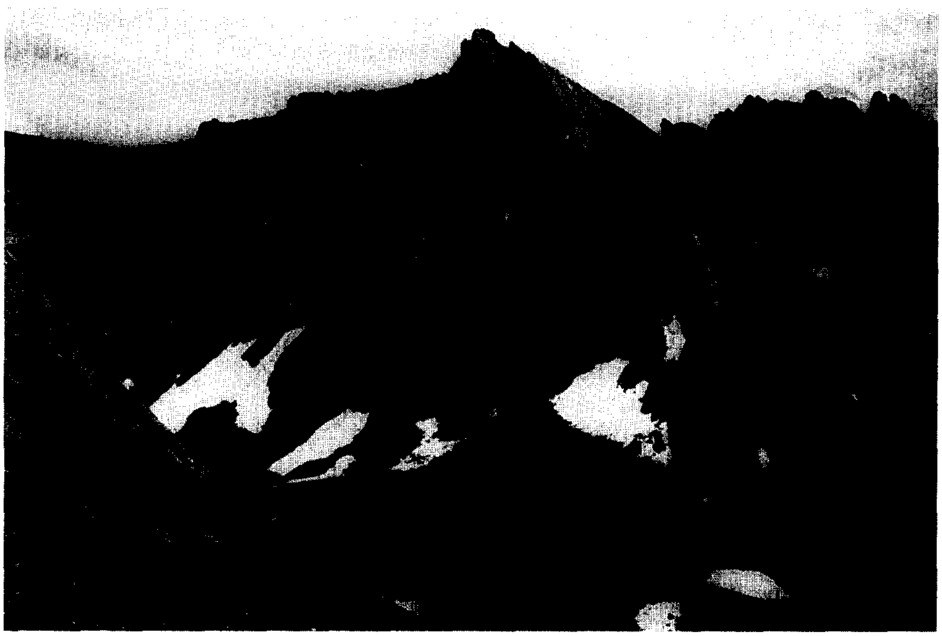

Fig. 3. Chutes on an orthoclinal slope in steeply dipping beds of Paleozoic limestone.

Fig. 4. A cataclinal dip slope in thick beds of Paleozoic limestone, where the rock slopes conform to the dip of bedding planes.

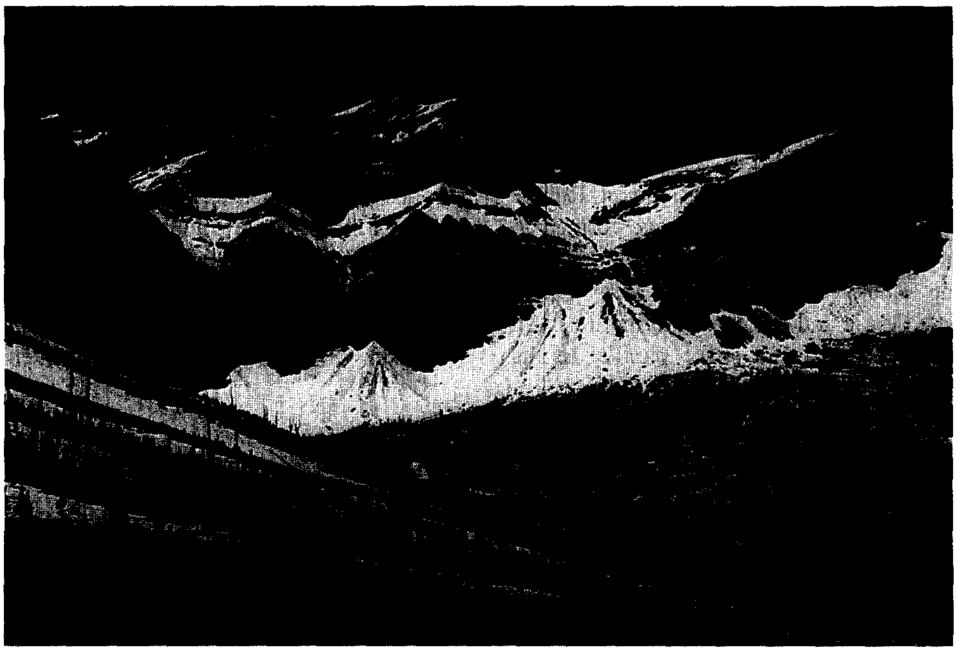

Fig. 5. A rock funnel (left) and an open cirque (right) on the anaclinal slopes of Mount Fortress.

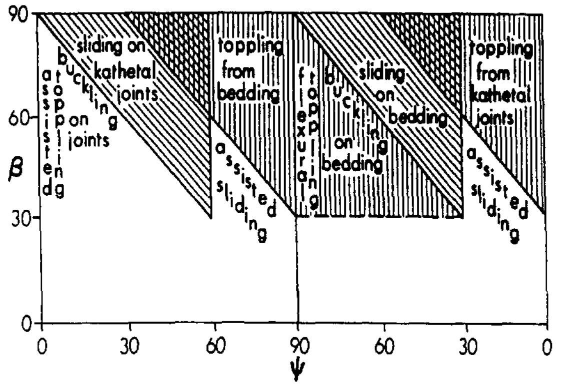

Fig. 6. Mass wasting process by dip of the bedding planes and gradient of the rock face for anaclinal and cataclinal slopes in sedimentary rock masses with $\phi = 30°$, $c' = 0$. Blocks on slopes in the lined areas can move under gravity alone (after Cruden, 1988).

tation of the discontinuities, we can hypothesize characteristic open rock basins for each structural class (Table 1). The remainder of this paper is a test of this hypothesized association between the structural and morphometric classifications of open rock basins.

3. Methods

The study sites are 56 open rock basins on dissected rockwalls in the Kananaskis area of the Front Ranges of the Alberta Rockies (Fig. 1). The Front Ranges are thrust-faulted mountain blocks. The peaks and high ridges are composed of resistant limestone and dolomite mainly of the Mississippian Rundle Group. The valleys and low ridges have formed in less resistant Mesozoic sandstones, siltstones, and shales of the Rocky Mountain and Spray River Groups and the Fernie and Kootenay Formations. All strata dip southwestward and strike parallel to the trend of the Ranges. The Front Ranges are examples of structurally controlled landforms, in which elements of the topographic relief are correlated with the bedrock geology (Sander, 1970, pp. 210–212).

Climatic data from 1966–73, collected about 100 m below timberline at Highwood Pass (Fig. 1), indicate a mean annual air temperature of about −2°C (Lester, 1974). The average number of days per year with frost is approximately 260. Snowfall accounts for roughly 60% of the annual precipitation. As a result, snow avalanches, debris flow, and snowmelt runoff are effective agents of coarse-sediment transport (Gardner, 1986), especially in open rock basins where snow and rock debris accumulate. The dominant geomorphic processes are solutional weathering of the calcareous substrates and low-magnitude, high-frequency rockfall (Gardner et al., 1983).

Data on the morphometry of the rock basins that we studied were derived from digital elevation models (DEM) as described in Sauchyn and Gardner (1983). The density of elevation sampling was about 500 points per km^2, but varied according to topographic complexity. Horizontal coordinates were expressed relative to a local control point and elevations were scaled such that the mouth of each basin had an elevation of zero. Maximum error for a single elevation is 0.7 m, discounting errors in the ground control, which are about an order of magnitude smaller. Because the coordinates are relative rather than absolute, imprecision in the scaling and orientation of stereo models, resulting from errors in ground control, is assumed to be small.

Ten morphometric indices were derived from the DEMs. The first five are measures of basin size and operationally defined as: (1) length: the planimetric length of the longest axis originating at the mouth of a basin; (2) width: the maximum dimension perpen-

Table 1
Processes that release rock blocks and characteristic rock basin(s) for each structural class

Structural class	Processes of release	Characteristic rock basin(s)
anaclinal	sliding on joints, toppling from bedding	funnels, open cirques
underdip	assisted sliding, flexural toppling	funnels, chutes
dip–overdip	sliding on bedding, toppling from joints	chutes
orthoclinal	assisted sliding, toppling from joints	chutes

Table 2
Minimum/maximum morphometric statistics by structural class (n)

Variable	Anaclinal (20)	Dip–overdip (7)	Orthoclinal (8)	Underdip (21)
length (m)	281.5/952.8	308.1/713.0	318.5/1055.5	311.2/871.4
width (m)	157.0/713.4	81.2/476.7	74.0/359.0	88.1/579.6
relief (m)	329.6/884.3	265.2/490.6	230.3/733.3	306.3/854.9
perimeter (m)	986.0/2922.5	753.5/2053.4	693.6/2457.7	820.3/2281.5
area (dam^2)	476.5/5450.2	181.4/2563.5	172.3/2509.6	303.3/2551.3
compactness	0.71/0.98	0.59/0.93	0.53/0.73	0.65/0.93
length/width	0.86/3.58	1.50/4.43	2.60/7.36	1.28/4.51
length/relief	0.61/1.27	0.66/1.45	1.00/1.48	0.83/1.32
width/relief	0.30/1.17	0.28/0.97	0.14/0.53	0.28/0.72
area/relief	107.4/616.3	63.44/522.50	74.81/342.21	80.89/319.04

dicular to the length axis; (3) relief: the difference between the maximum and minimum elevations; (4) area: the planimetric area encompassed by the basin perimeter; and (5) perimeter: the cumulative distance between the coordinates on the boundary of the open rock basin. The other five indices are shape parameters: (6) compactness (Blair and Bliss, 1967) is defined as the ratio of basin area to the sum of the moments of inertia of infinitesimal area elements ($r^2 dA$, where r is the distance of an area element from the basin centroid); it is relative to the compactness of a circle and thus varies between zero and one; (7) the ratio of length to width (elongation) is an additional measure of planimetric shape, and the ratios of (8) length to relief, (9) width to relief, and (10) area to relief are expressions of hypsometry or three-dimensional shape.

Bedding dip and strike were measured with a Brunton pocket transit at accessible locations in the basins. The mean values of up to ten measurements were used to classify each location. Strike values range through less than 10°. Dip values within a basin may have a range of up to 50° because of local folding of the bedding. Measurement errors have been discussed by Cruden and Charlesworth (1976).

The anaclinal and underdip walls of strike valleys dominate the regional physiography (Cruden and Eaton, 1987). Thus, these structural classes account for 41 of the 56 open rock basins in our study. Differences in sample size and variance among structural classes prevent the use of parametric statistical methods for the morphometric analysis of rock basins. Therefore, testing of the hypothesized associations between the structure and morphometry of the rock basins is based on the nonparametric analysis of the distribution of the rank scores of the morphometric statistics among structural classes (SAS NPAR1 WAY Procedure; SAS Institute Inc., 1988). Specifically, nonparametric analysis of variance (ANOVA) is first used to test the null hypothesis of no significant difference in the distribution of rank scores among and between structural classes. Then, the ranked morphometric data are compared between pairs of structural classes using a series of two-tailed Wilcoxon rank sum tests.

4. Results

The sizes and shapes of the open rock basins are summarized in Table 2, where minimum and maximum values are listed for the ten morphometric

Table 3
Nonparametric analysis of variance among structural classes

Form variable	F value	Prob. > F
length	4.37	0.0082
width	6.48	0.0009
relief	5.01	0.0041
perimeter	4.01	0.0122
area	4.51	0.0071
compactness	21.99	0.0001
length/width	16.30	0.0001
length/relief	10.89	0.0001
width/relief	7.02	0.0005
area/relief	4.64	0.0061

Structural classes: anaclinal ($n = 20$); dip–overdip ($n = 7$); orthoclinal ($n = 8$); underdip ($n = 21$).

Table 4
Results of Wilcoxon rank sum tests

Variable	Paired structural classes					
	a/d	o/a	u/a	u/d	o/d	o/u
length				*	*	
width	* *	*	*	*		
relief	* *			* *	*	
perimeter	* *			*		
area	* *			*		
compactness	* *	* * *	* * *			* *
length/width	* *	* * *	* * *			* *
length/relief	*	* *	*	*		* *
width/relief	*	* *	* *			
area/relief	* *	*		*		

Structural classes: anaclinal (a) ($n = 20$); dip–overdip (d) ($n = 7$); orthoclinal (o) ($n = 8$); underdip (u) ($n = 21$).
Probability of a larger $|t|$: * < 0.05; * * < 0.01; * * * < 0.001.

variables by structural class. The results of the nonparametric ANOVA are in Table 3. Variation in every morphometric measure of the rock basins is significantly ($\alpha < 0.05$) greater among the structural classes than within them. The more significant differences are in shape rather than size.

Table 4 gives the results of the two-tailed Wilcoxon rank sum tests of the null hypothesis of no difference in morphometry between pairs of structural classes. All of the significant ($\alpha < 0.05$) differences in size involve the basins in the dip–overdip and anaclinal categories, because they are smaller and wider, respectively, than the basins in the other structural classes. The anaclinal basins account for most of the differences in shape. They are significantly more compact (less elongate) and steeper (lower length/relief), and have higher width/relief and generally more area/relief. Thus, anaclinal basins are morphologically distinct from orthoclinal and dip–overdip basins, which are not significantly ($\alpha > 0.05$) different from one another.

The underdip basins are more compact (less elongate) and steeper than orthoclinal basins and have lower length/relief and higher area/relief than dip–overdip basins, but share only one shape characteristic (area/relief) with the anaclinal basins. This variation in morphometry by structural class is apparent when compactness, a planimetric variable, is plotted against the hypsometric variables width/relief (Fig. 7) and length/relief (Fig. 8). Compactness is the most discriminating parameter of shape (Tables 3 and 4) and is strongly correlated ($\alpha < 0.001$) with log(length/relief). Sauchyn and Gardner (1983) used compactness and area/relief to classify rock

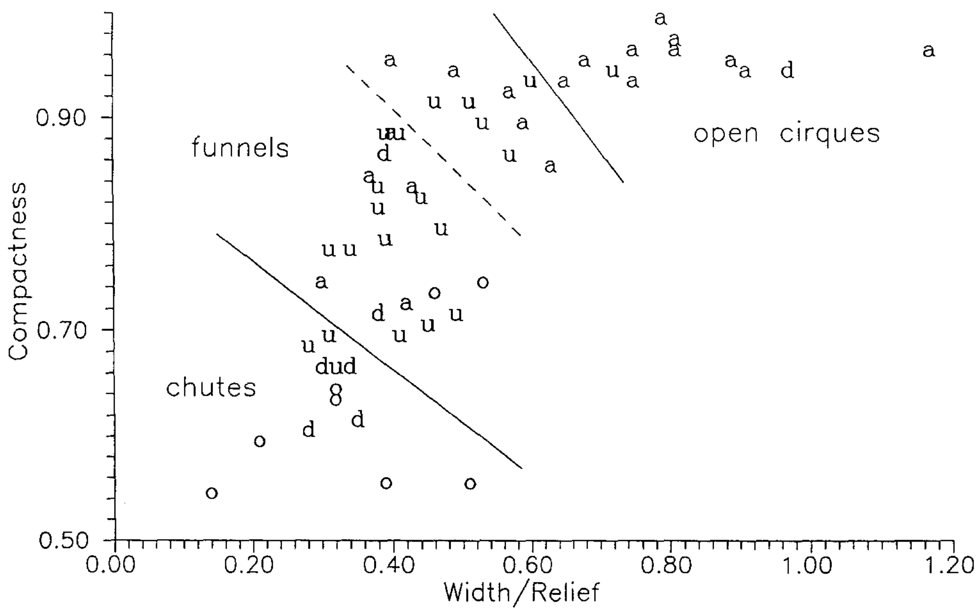

Fig. 7. A plot of compactness versus width/relief. The open rock basins are plotted with symbols designating the structural class: orthoclinal (o), anaclinal (a), dip and overdip (d), and underdip (u).

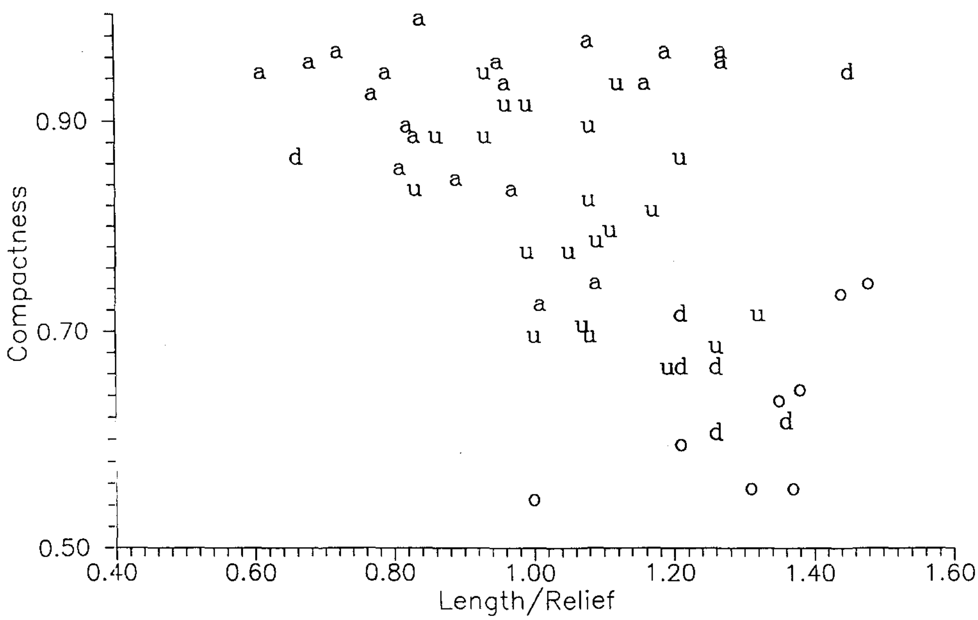

Fig. 8. A plot of compactness versus length/relief. The open rock basins are plotted with symbols designating the structural class: orthoclinal (*o*), anaclinal (*a*), dip and overdip (*d*), and underdip (*u*).

basins into chutes, funnels, and open cirques. Width/relief, however, accounts for more differences in shape among structural classes than area/relief (Tables 3 and 4). A cluster analysis of the width/relief and compactness data reveals the stratification of the sample into chutes, funnels, open cirques, and a few basins with intermediate morphology. Fig. 7 shows the association between the morphological and structural classes: a strong tendency for chutes on orthoclinal, dip and overdip slopes, funnels on underdip and anaclinal slopes and open cirques on anaclinal slopes. It also illustrates the significant ($\alpha < 0.05$) positive correlation between compactness and width/relief.

Length/relief, the reciprocal of average basin gradient, is an independent measure of hypsometry, that is, uncorrelated with width/relief and area/relief. It is negatively correlated ($\alpha < 0.05$) with compactness (Fig. 8). Low compactness and high length/relief characterize all the orthoclinal basins and most of those in the dip–overdip class. Anaclinal basins have the opposite characteristics, although the most compact basins also have the largest range of average gradients. As with the other parameters of shape, underdip basins span the middle of the continuum, overlapping with orthoclinal and dip–overdip basins at one end and anaclinal basins at the other.

5. Discussion

The results of this study support the hypothesized differences in the morphometry of open rock basins among structural classes. These differences can be explained in terms of the mechanics of rock block failure and the linkages among structure, landform and process in sedimentary rock masses and periglacial environments. The relative orientations of rock slopes and penetrative discontinuities determine the mode of release of joint blocks and, thereby, the nature and rate of rockwall retreat by non-catastrophic mass wasting. Characteristic open rock basin morphologies have distinct structural settings, although no direct or obvious link exists between the angles of bedding planes and morphometric parameters, such as the length to width ratio of an open rock basin.

Sliding on bedding is the dominant mass wasting process on dip and overdip slopes. The open rock basins in this structural class, however, are relatively small and uncommon because, where slope gradients exceed the basic friction angle, dip–overdip slopes tend to fail by catastrophic mass wasting (rockslides and large rockfalls) (Cruden, 1988). Continuous mass wasting occurs on overdip slopes by toppling from kathetal joints. On dip and overdip rockwalls, rock blocks slide from exposed beds, including those on the walls of incipient open rock basins formed at discontinuities with a more favourable orientation for the release of rock blocks. These chutes then evolve by sliding of blocks from the floor, and sliding and toppling from the walls.

On the 21 underdip slopes, the beds dip 75–90° and 90° at seven sites. Cruden (1989) has shown that toppling is a possible mode of movement for rock blocks on such slopes. Rock funnels develop as blocks of rock topple and fall from the walls of chutes and as divides between adjacent chutes are eliminated (Rapp, 1960). On anaclinal slopes, sliding on kathetal joints and toppling from bedding generate rockfalls from moderately and steeply dipping beds, respectively. Both modes of failure may occur on slopes above about 60°. The rock funnels and open cirques on anaclinal rockwalls are typically wide and compact, and supply debris to large active talus cones. The concave profile is characteristic of erosional landforms in hard jointed rock, where resistance to quasi-continuous mass wasting is relatively consistent across the rock mass. Landforms with similar morphology include glacial cirques and amphitheater valley heads in fluvial landscapes.

The strike of dipping strata relative to the aspect of the rockwall determines whether beds of differing stability form chutes and buttresses (orthoclinal slopes), or extend across rockwalls (cataclinal and anaclinal slopes) and retreat at uniform rates to form funnels and open cirques. The optimal structural setting for the development of large compact open cirques is anaclinal, and the least favourable is cataclinal dip and overdip slopes. The relationship of dip and strike to the slope of rockwalls has definite thresholds that define structural classes. On the other hand, there are no obvious limits to morphological classes. The continuous variation in morphometry from low compactness and area/relief (chutes) to high compactness and low area/relief (funnels) to high compactness and area/relief (open cirques) corresponds to a change in dominant structural class from orthoclinal to dip–overdip to underdip to anaclinal. An anaclinal structure is associated with high compactness and the entire range of width/relief, spanning the gradation from funnels to open cirques.

Variation in morphometry not explained by differences in structural class may reflect the influence of topoclimate and other aspects of geologic structure. For example, an inventory of mass-wasting events in the Kananaskis area by Gardner (1983) indicated that rockfalls are most common on north- to east-facing slopes. Snow and ice are a greater geomorphic factor on these slopes, given that differences in the receipt of solar energy and depth of snow accumulation are a function of aspect. Snow avalanching and snowmelt runoff assist toppling and sliding, the development of chutes from bedrock channels, and rockwall dissection, in general, by removing weathered rock. The growth of rock basins further promotes the storage of snow, water and ice. Because the topoclimate and structure of the Front Ranges vary systematically with aspect, they cannot be easily separated in the explanation of rockwall process and morphology. For example, north- and east-facing slopes often have an anaclinal structure, and thus the geology and topoclimate favour non-catastrophic mass wasting.

Geologic structures superimposed on the regional fabric may cause rock basins to differ morphologically from others in the same structural class. The anomalous basins in Figs. 7 and 8 are the open cirque with a dip–overdip structure, two orthoclinal slopes with intermediate compactness and area/relief, and two anaclinal basins with compactness below 0.80, including one that qualifies as the most compact chute. These five anomalous basins are located in adjacent valleys in the Kananaskis Range, where several folds and reverse faults trend transverse to the axes of the valleys (McMechan, 1988). They are complex structurally controlled slopes as opposed to strength equilibrium slopes (Selby, 1982), where the structural control is expressed as resistance to sliding, toppling and falling of joint blocks. Finally, morphological differences within a structural class could result from variation in the strike and dip of beds and fractures across rockwalls, such that parts of an open rock basin might have a different structural setting.

This study examined the influence of the relative orientation of bedding planes on the mesoscale morphometry of mountain rockwalls. Elevations were purposefully sampled to capture the morphometry of open rock basins. Other elements and scales of geologic structure control the form of rock slopes: the geometry of folds and faults, the detailed profiles of cliffs, and the shapes of entire mountains. The results presented here for open rock basins suggest a direction for further research on structural control of the morphometry of rock slopes at various scales using digital elevation data.

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