Exhaustion and steady state models for predicting landslide hazard in the Canadian Rockies

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ABSTRACT

The temporal distribution of landslides can be evaluated by steady state and exhaustion models. The probability of landsliding remains constant through time in the steady state model but the probability decreases in the exhaustion model as more slopes fail . Rock sliding down bedding surfaces on overdip slopes exhausts hazardous sites to leave stable dip-slope landforms in Kananaskis Country in the Canadian Rockies. The distribution of rock slides in this area can be better explained by the exhaustion model than by the steady state model.

INTRODUCTION

This paper develops statistical models of the temporal distribution of rock slides in the Canadian Rockies based on the work in Kananaskis Country, Alberta by Cruden and Eaton (1987) and Cruden, *et al.* (1988). We consider only rock slides down bedding planes in the model because most of the large landslides in the Canadian Rockies slid down these penetrative discontinuities. Also, the mechanisms of sliding along penetrative discontinuities have been studied more extensively and the processes are better understood than other types of landslides, such as topples (Hu and Cruden, 1993) and slides across penetrative discontinuities (Hu and Cruden, 1992b). Our terminology follows Varnes (1978) and Cruden (1991).

Kananaskis Country is in the Front Ranges of the Canadian Rocky Mountains. Highway 40 runs south from the Trans-Canada Highway through Kananaskis Country (Fig. 1). The downhill skiing events of the 1988 Winter Olympic Games were held at Mt. Allan, increasing the popularity of the area for recreation. Many slope movements have displaced rock masses and deposited them at the toes of slopes since the last glaciation. Studies of the spatial and temporal distributions of these slope movements and potential slope movements have included modes and magnitudes of rock mass movements and structural, lithological and topographic controls of the movements (Gardner, 1980; Cruden and Eaton, 1987; Hu, 1987).

Gardner (1980) related the frequencies and magnitudes of rock slope movements and suggested a frequency of one major movement every 5000 years in a 100 km^2 area based on field monitoring in the Highwood Pass in Kananaskis Country. Eaton's (1986) mapping of the displaced materials of all slope movements on 1:15840 aerial photographs over 880 km^2 indicated that rock slides down bedding planes, the penetrative discontinuities in the rock slopes, are the most hazardous type of movements in terms of magnitude and travel distances. Hu (1987) studied all the potential rock slides along bedding planes in the same area as Eaton (1986). Apparent cohesion along bedding planes seems to have prevented these potential rock slides from sliding.

Evans and Gardner (1989) reviewed the studies of the distribution of major rock avalanche events in postglacial time in the Canadian Cordillera. Gardner (1980) and Luckman (1981) have suggested that most rock avalanches in the Cordillera occurred in the immediate postglacial period. Evans and Clague (1988) pointed out that many historic rock avalanches, including half of those in western Canada in the last 30 years, had taken place in glacierized mountains. All these authors have assumed, however, that for predictive purposes rock sliding is a steady state process and the probability of rock sliding was constant in postglacial time.

Using the prehistoric rock slides and sites of potential rock slides in Kananaskis Country, Alberta as data, this paper examines the steady-state model and introduces a new model, the exhaustion model, which predicts the probability of landsliding decreases after slopes move.

PHYSICAL ENVIRONMENT

BEDROCK GEOLOGY

The study area (Fig. 1) is cut by thrust faults striking northwest-southeast; folds run subparallel to the thrust faults (Bielenstein *et. al.,* 1971). Palaeozoic sedimentary rocks uplifted by thrust faults form the mountain ranges and relatively weaker and younger rocks floor the valleys. Rock slides commonly occur in the sandstones of the Permo-Pennsylvanian Rocky Mountain

Group and the carbonates of the Mississippian Rundle Group, the Devonian Palliser Formation and Fairholme Group (Bielenstein *et. al.,* 1971). In addition to the bedding planes which are penetrative, the rocks contain at least two joint sets, both perpendicular to bedding planes. The strikes of the joint sets are respectively perpendicular and parallel to the strike of the bedding.

SURFICIAL GEOLOGY

Several glaciations in the Quaternary have shaped the mountains (Jackson, 1981). Bedrock slopes were steepened by the glaciations and tills were deposited on valley floors. Since the end of the last glaciation about 10,000 years ago, many rock masses were displaced from bedrock slopes and deposited at the base of the bedrock slopes. Talus also lies at the base of slopes as a result of fragmental rockfalls. Most of the displaced materials and talus are above tree line.

CLIMATE

Climatic stations in the valleys of the study area record mean annual temperatures from 1.4° to 3.5° C and precipitation amounts from 471 mm to 657 mm with about 45% falling as snow (Environment Canada, 1981). The area is covered by snow except in June, July and August, when snow patches remain only at higher elevations. Peltier's classification (1950) would suggest weak frost weathering in the area increasing to moderate at higher elevations and moderate chemical weathering supplemented by carbonate solution. These processes may eventually destroy apparent cohesion along bedding surfaces.

SLOPE TYPES

Powell (1875) divided slopes in sedimentary rocks by the orientations of the bedding and of the slopes into anaclinal, cataclinal, orthoclinal and plagioclinal slopes. On anaclinal slopes bedding dips in the direction opposite to the slope whereas on cataclinal slopes the bedding dip is in the same direction as the slope. Cataclinal slopes can be further divided into overdip slopes where slopes exceed bedding dips, dip slopes where slopes equal bedding dips and underdip slopes which are less than bedding dips. Orthoclinal slopes are perpendicular to bedding dips and plagioclinal slopes are oblique to bedding dips. The type of slope movement differs with type of slope. Sliding down bedding planes occurs only on cataclinal overdip slopes where bedding planes dip in the same directions as the slopes and the bedding dip is less than the slope angle (Cruden 1988).

Sliding along bedding planes on overdip slopes can be modelled by sliding blocks on inclined planes. In the simplest model, the block slides when the dip of the bedding plane is greater than the friction angle of the block on the plane and there is no cohesion or forces other than gravity. Displacement of rock masses on overdip slopes produces dip slopes which are parallel to slope surfaces and stable with respect to sliding along bedding surfaces.

ROCKSLIDES AND POTENTIAL ROCKSLIDES

During the last glaciation, many overdip slopes were formed or steepened by glacial erosion. Rock mass movements on the steepened slopes after the last glaciation have produced much displaced material at the base of the slopes. Eaton (1986) mapped 228 slope movements with volumes larger than 10^3 m^3, and 67 of them were slope movements on overdip slopes. Slides on these slopes were predominantly translational slides. The largest rock slide, the Palliser rock slide (Fig. 2), over 50 x 10^6 m^3, was on an overdip slope and left a dip slope of over 30°. Cruden and Eaton (1987) concluded that the probability of a major landslide on an overdip or dip slope is at least four times that on an anaclinal slope, the next highest probability (Fig. 3).

Hu (1987) mapped all the overdip slopes in Eaton's (1986) study area. Fourteen potential rock slides along bedding surfaces were identified among these slopes. They had bedding dips greater than the basic friction angles of potential sliding surfaces; Figure 4 is a view of one of the potential slides. Basic friction angles were estimated locally from the grain size and dolomite content of the carbonate rocks (Cruden and Hu, 1988) and from on-site tests of the sandstones (Hu and Cruden, 1992a). Cohesion of intact rock blocks can be estimated from uniaxial compressive strengths of the rocks and friction angles (Goodman, 1989, p. 82, Equation 3.9). Apparent cohesion along bedding surfaces at these sites could then be back-calculated to be less than 0.1% of cohesion of intact rock blocks (Figure 5). Flexure slip along bedding surfaces during folding of strata had apparently greatly reduced the cohesion along bedding planes. Rock masses at these sites have not slid because of the remaining apparent cohesion. However, cohesion will be destroyed eventually by weathering processes and these potential rock slides will slide in the future.

MODELS OF THE DISTRIBUTION OF ROCK SLIDES IN KANANASKIS COUNTRY

The steady state model (Evans and Gardner, 1989) of the temporal distribution of rock slides down bedding planes in Kananaskis Country would assume the events to be random events in time. We now compare this model to a new model, the exhaustion model, which makes a similar assumption.

STEADY-STATE MODEL

In this model the population of hazardous slopes is assumed to be large and the hazard (Varnes, 1984) of a rock slide in the area is not changed by the passage of time or by previous rock sliding events. The steady state model assumes that the distribution of intervals between rock sliding events does not vary through time and can be estimated from numbers of rock slides during a period of time.

For example, the average interval between rock slides in Kananaskis Country after the last glaciation can be calculated by dividing the number of post-glacial rock slides into 10,000 years, the assumed duration of post-glacial time in the Rockies. Because the number of rock slides identified is 67, the return period of rock slide events is 150 years (10,000 years divided by 67) or a rate of occurrence of 6.6×10^{-3}/year. No large rock slides are known from the 130 year history of the area.

EXHAUSTION MODEL

In this model the post-glacial rock slides and the sites of potential rock slides are assumed to be from the same finite population of slopes which are assumed to rupture once. Rock slide hazard is confined to the potential rock slide sites. If a rock slide eliminates an overdip slope, there is no further risk of rock sliding at the site. So, while the hazard of each potential rock slide remains constant, the area under hazard from slides declines with each rock slide. If the exhaustion process continues without further disturbance, all the potential rock slides will eventually rupture and then the hazard of further rock slides becomes zero. The exhaustion model applies after the toes of slopes are eroded and erosion stops, the slopes are thus "abandoned" in Hutchinson's (1973) terminology.

In Kananaskis Country, the last glaciation created and steepened many overdip slopes. The retreat of the glaciers removed the support of the toes of these slopes in a short period about 10,000 years ago, other processes eroding the toes of slopes after the glacial retreat are insignificant compared with rock sliding. Besides rock slides there are no other obvious erosional forms of non-glacial origin on the scale of the glaciated valleys.

The occurrence of rock sliding at each overdip slope is independent of other overdip slopes and the risk of rock sliding in an area decreases as more and more overdip slopes are ruptured. The temporal distribution of rock sliding can be modelled by the negative exponential distribution which describes random events having uniform probability of occurrence with time. It follows a model similar to that used to describe the decay of activity of radioactive substances. If there are n potential rock slide sites which rupture at a rate λ, then the number of the sites, Dn, which rupture in an interval time, Dt, is

$$Dn = -n\lambda\, Dt$$

For small changes, dn, in dt,

$$dn/n = -\lambda\, dt, \text{ then}$$

$$\log_e n = -\lambda t + C$$

If $n = n_0$ when $t = 0$, then $C = \log_e n_0$ and

$$\log_e(n/n_0) = -\lambda t \qquad (1)$$

In Kananaskis Country, $n_0 = 67+14=81$, $n = 14$ and $t = 10{,}000$ years in Equation (1),

So $\log_e(14/81) = -\lambda \times 10^4$ years

$$\lambda = 1.8 \times 10^{-4}/\text{year};$$

$1/\lambda$, 5700 years, is the average endurance or life of a potential slide site, the time from deglaciation to sliding.

The rock sliding rate given by the exhaustion model in Kananaskis Country at present is $n\lambda = 14 \times 1.8 \times 10^{-4}$/year $= 2.4 \times 10^{-3}$/year or the return period is about 410 years. The return period is 2.7 times longer than that predicted by the steady state model, 150 years.

DISCUSSION

Previous evaluations of the rock slide probability in the Canadian Rockies (Gardner, 1980; Evans and Gardner, 1989) were based on the assumption of steady state processes. The steady state model does not consider any particular mechanism of rock mass movement. Detailed mapping of rock slides and potential rock slides in Kananaskis Country (Eaton 1986, Hu 1987) revealed that slides were most frequent on overdip slopes and produced dip slopes, a stable slope type. There is generally no risk of sliding on a dip slope. The sliding processes are thus not steady state but exhaustive in Kananaskis Country. The exhaustion model, based on detailed studies of rock slide mechanisms, allows better assessment of the hazard.

The exhaustion model can be applied to slopes which, in the terminology of Selby (1974), are adjusting their form to a constant state after a landforming event. In Kananaskis, glaciation was a landforming event which produced overdip slopes which adjust to stable dip slopes by landsliding over time. The exhaustion model does not assess slope movements in the area by processes other than sliding along penetrative discontinuities.

CONCLUSIONS

The choice of models for extrapolating landslide frequency into the future can have significant impact on the assessment of landslide hazard. Preferring an exhaustion model to a steady state model reduces the estimated hazard of rock sliding in Kananaskis Country by a factor of 2.7.

Exhaustion models are appropriate where the number of potential slide sites is limited and when rock slides eliminate the unstable slope, here an overdip slope, to produce a stable characteristic landform, a dip slope in this case.

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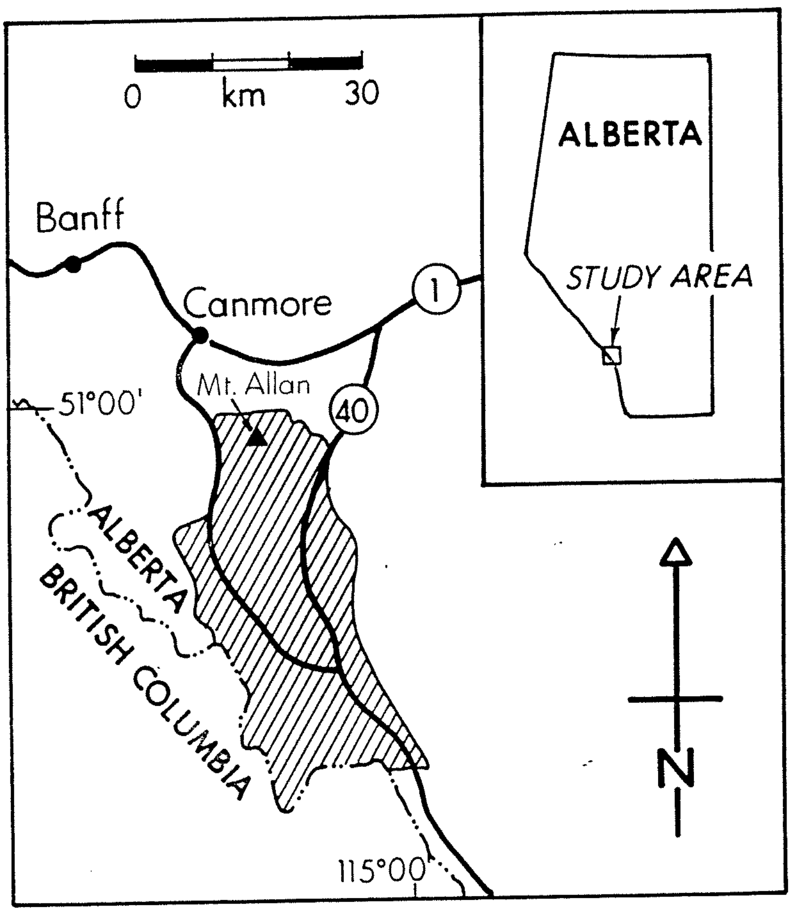

Fig. 1 The location of Kananaskis Country (shaded).

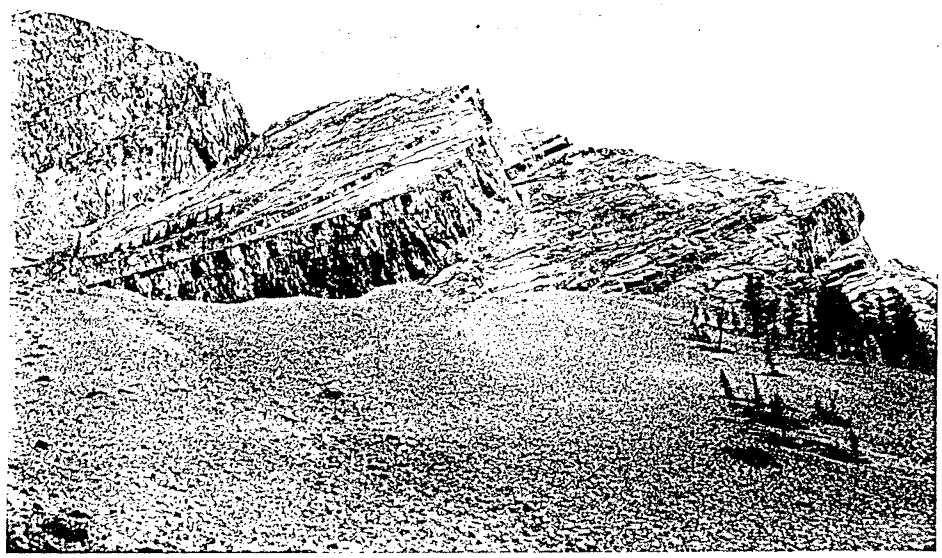

Fig. 2 Palliser rockslide view from its displaced material. The rupture surface of an older rock slide is in the right of the photograph (Cruden and Eaton, 1987).

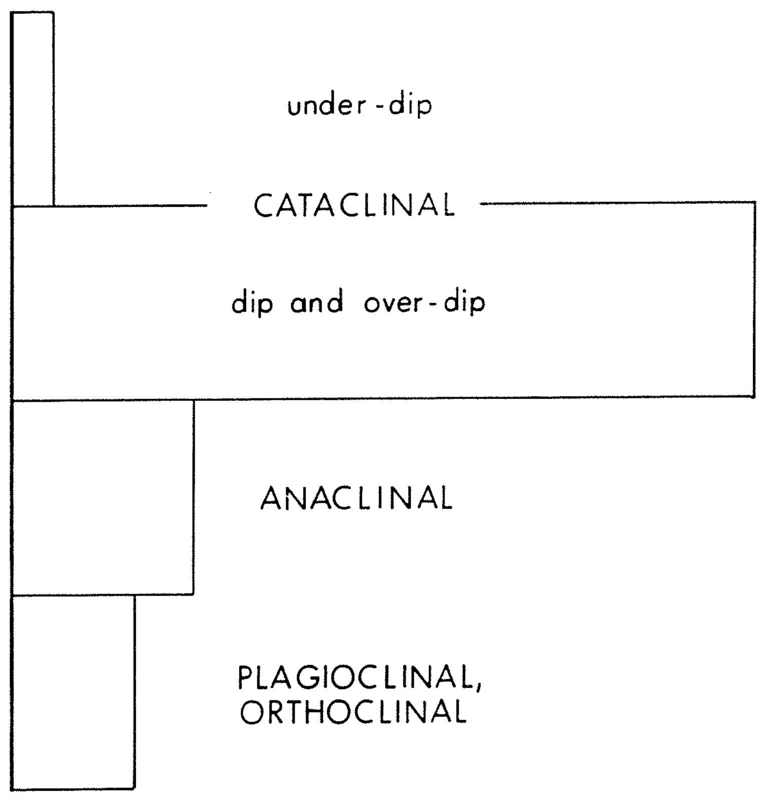

Fig. 3 Histogram of the relative frequency of a major rock slide on slopes of different types in Kananaskis Country (Eaton, 1986).

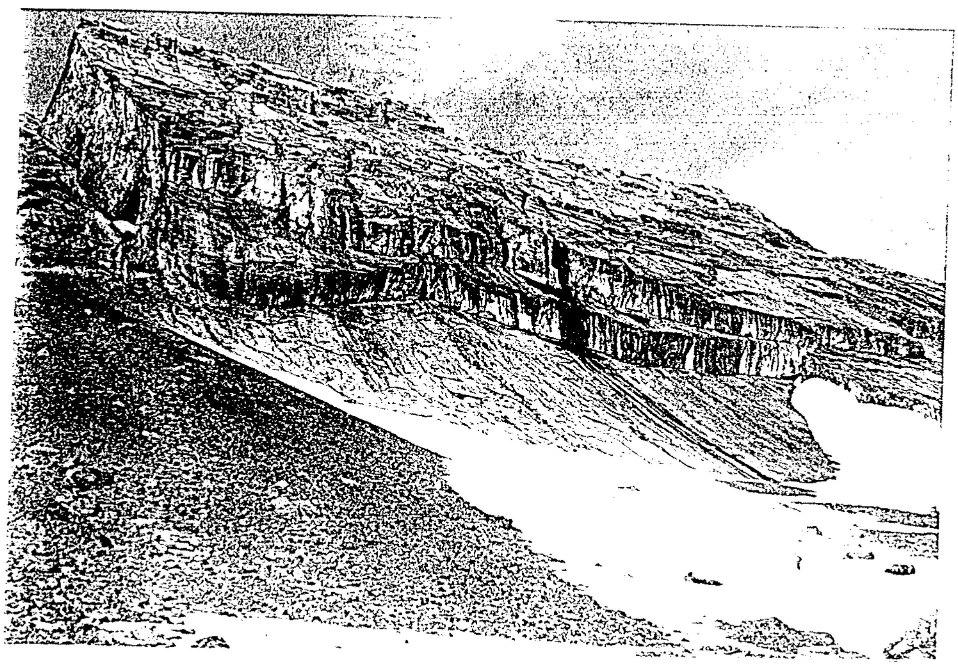

Fig. 4 Potential rockslide at Burstall Pass. Portions of bedding planes, potential rupture surfaces are exposed and potential displaced masses overlie the bedding planes. The figure on the snow patch in the lower right hand corner of the photograph indicates the scale.

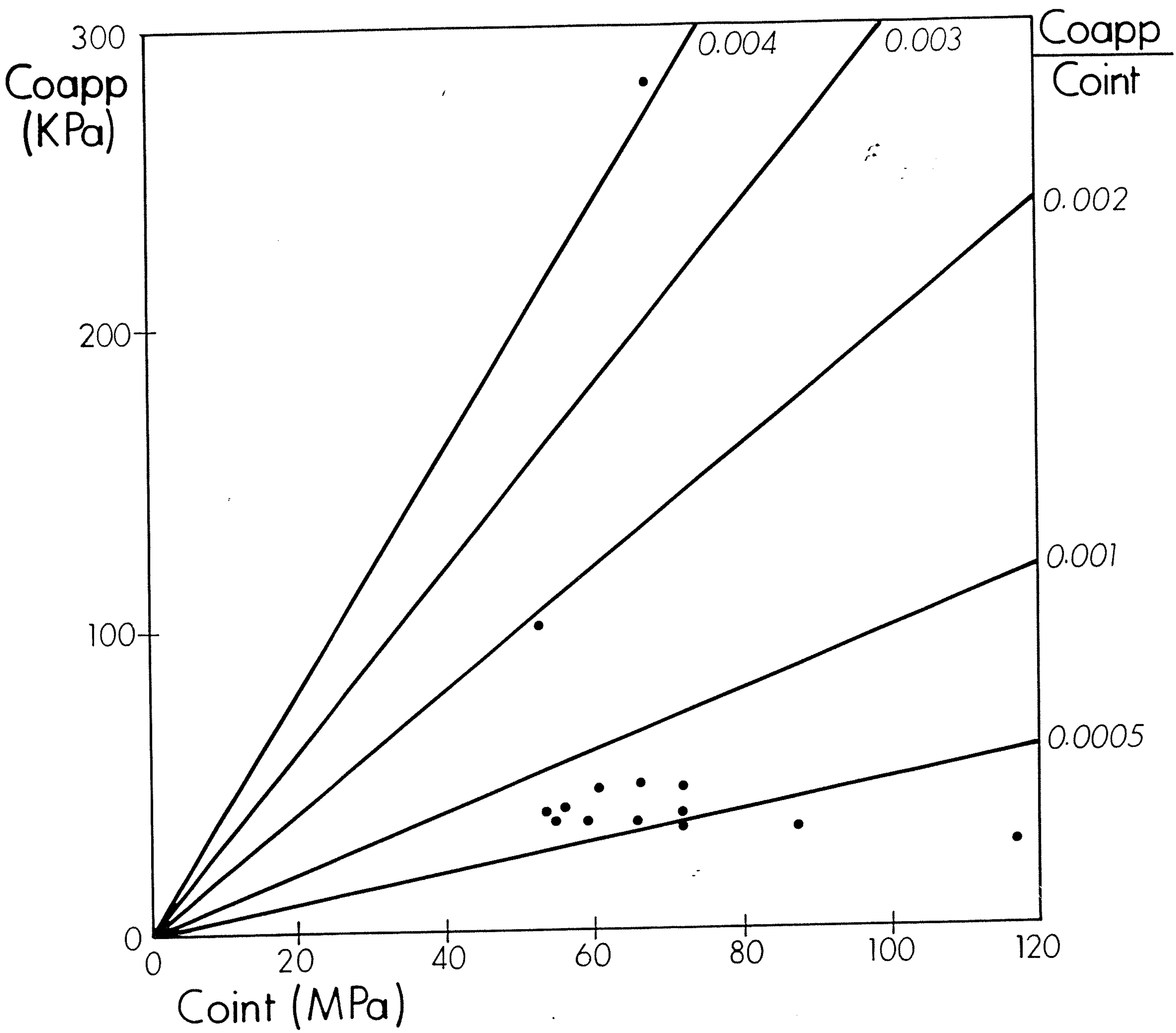

Fig. 5. Coapp; the lower bounds of cohesion along bedding surfaces calculated by back analyses, compared to Coint; the cohesion of the intact rock blocks, on 14 overdip slopes. We have drawn lines for ratios of Coapp to Coint ranging from 0.4% to 0.05%. 12 of the 14 sites lie below the 0.1% line.

Fig. 2 Palliser rockslide

Fig. 4 Potential rockslide at Burstall Pass. The portion of the bedding plane, potential sliding plane, is exposed and the potential sliding mass is above the bedding plane.