The Heather Hill landslide: an example of a large scale toppling failure in a natural slope

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This paper is an inquiry into the suspected relationship between toppling and large deep-seated landslides along the Beaver Valley, Glacier National Park, British Columbia. The study area includes the Heather Hill landslide, one of several in the valley, and adjacent slopes that show varying degrees of toppling disturbance. The development of the Heather Hill landslide is simulated using the distinct element method of numerical analysis. The rock mass is modelled using deformable columns whose boundaries represent a coarse approximation of *in situ* discontinuity patterns. An intercalated change in the predominant lithologies and a concomitant change in discontinuity spacings are modelled by varying column thickness and material properties. The analysis confirms that a deep-seated failure surface can develop as a result of the toppling process. The intercalated change in lithologies and the related change in discontinuity spacings account for the curvilinear failure surface and the headscarp position of the Heather Hill landslide. These variables are believed to also control the overall distribution of landslides in the Beaver Valley. The paper demonstrates that the distinct element method provides an effective basis for quantitative analysis of large scale toppling. Many more applications will be needed to refine the geometric and material property generalizations used in this study. Nevertheless, the method appears to offer considerable promise for elucidating problems of rock slope behaviour in both slope engineering and geomorphology.

Key words: toppling, landslide, British Columbia, mountains, numerical modelling, distinct element method.

Cet article présente une étude de la relation possible entre les mouvements de bascule et les glissements profonds dans la vallée de Beaver River, Glacier National Park, Colombie-Britannique. La région étudiée comprend le glissement de Heather Hill, un des nombreux dans la vallée, et les talus adjacents qui exhibent des désordres par bascule à des degrés variables. Le développement du glissement de Heather Hill est simulé par calcul numérique au moyen de la méthode d'éléments distincts. La masse de roche est modélisée par des colonnes déformables dont les limites représentent une approximation grossière des patrons de discontinuité *in situ*. Un changement intercalé dans les lithologies prédominantes, et un changement concomitant dans les espacements des discontinuités sont modélisés en variant l'épaisseur de colonne et les propriétés du matériau. L'analyse confirme qu'une surface de rupture profonde peut résulter du processus de bascule. Le changement intercalé des lithologies et le changement résultant des espacements des discontinuités expliquent la surface de rupture curvilinéaire et la position de la crête de l'escarpement du glissement de Heather Hill. L'on croit que ces variables contrôlent également l'ensemble de la distribution des glissements dans la vallée Beaver. Cet article démontre que la méthode d'éléments distincts fournit une base efficace pour une analyse quantitative de bascule à grande échelle. Plusieurs autres applications vont être requises pour raffiner les généralisations des propriétés de géométrie et du matériau utilisées dans cette étude. Néanmoins, la méthode semble offrir beaucoup de potentiel pour élucider des problèmes de comportement de talus rocheux tant en géomorphologie que pour la conception de talus.

Mots clés : bascule, glissement, Colombie-Britannique, montagnes, modèle numérique, méthode d'éléments distincts.

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Introduction

Toppling is a well-documented mass wasting process than can occur at any scale (de Frietas and Watters 1973). Geomorphologists have reported examples of large scale toppling in natural slopes and have recognized a possible association between the toppling process and some types of sackung (Holmes and Jarvis 1985; Bovis 1982, 1990; Savage and Varnes 1987; Zischinsky, 1966). Geotechnical engineers, although familiar with toppling in engineered slopes, are less acquainted with natural toppling. Available methods of toppling analysis for design applications are limited to small scale engineered slopes. Best known is the limit equilibrium method described by Goodman and Bray (1976). No method of analysis has yet been developed for large scale toppling of natural slopes. The effect of large scale toppling on a rock mass is typically not considered in engineering design, even though variations in discontinuity orientations, hydraulic conductivity, RQD, and shear fabric in rock masses comprising some natural slopes may be a predictable manifestation of toppling.

This paper and a companion paper (Pritchard and Savigny 1990) represent the initial part of a research program with the following objectives: first, to develop a versatile method of toppling analysis and second, to investigate the depth to which toppling influences rock masses comprising natural slopes in mountainous terrain and the mechanical and morphological nature of its effect. Pritchard and Savigny (1990) reviewed the toppling process and alternative methods of analysis, provided a rationale for selection of the distinct element method, and verified the method using three examples of toppling failure. This paper provides a summary of a detailed study of the Heather Hill landslide, one of several in the Beaver River Valley of Glacier National Park, and presents the results of a distinct element analysis where the effect of toppling in development of the landslide is evaluated.

Beaver Valley is the eastern approach to Rogers Pass, British Columbia (Fig. 1), a narrow transportation corridor first traversed by Canadian Pacific Railway (now CP Rail) in 1885. The Trans Canada Highway was built in the 1960s,

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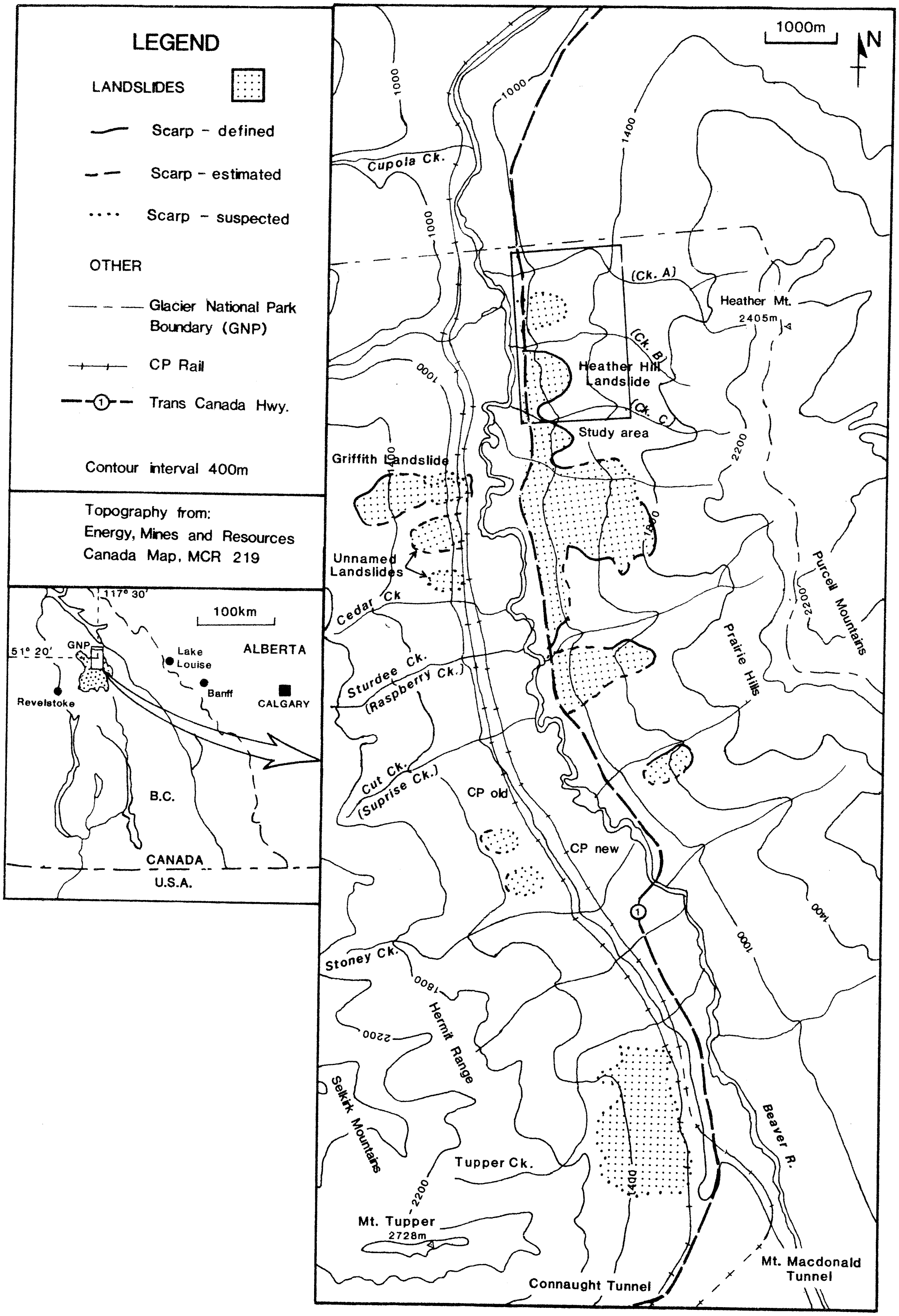

FIG. 1. Topographic map of the Beaver Valley showing locations of deep-seated landslides and study area (after Pritchard *et al.* 1988).

and in the 1980s, CP Rail constructed a second line as part of its larger Rogers Pass grade revision project (Savigny *et al.*, in press).

Large, deep-seated landslides on the Beaver Valley slopes cause maintenance problems on both the CP Rail grade and the Trans Canada Highway (EBA Engineering Consultants

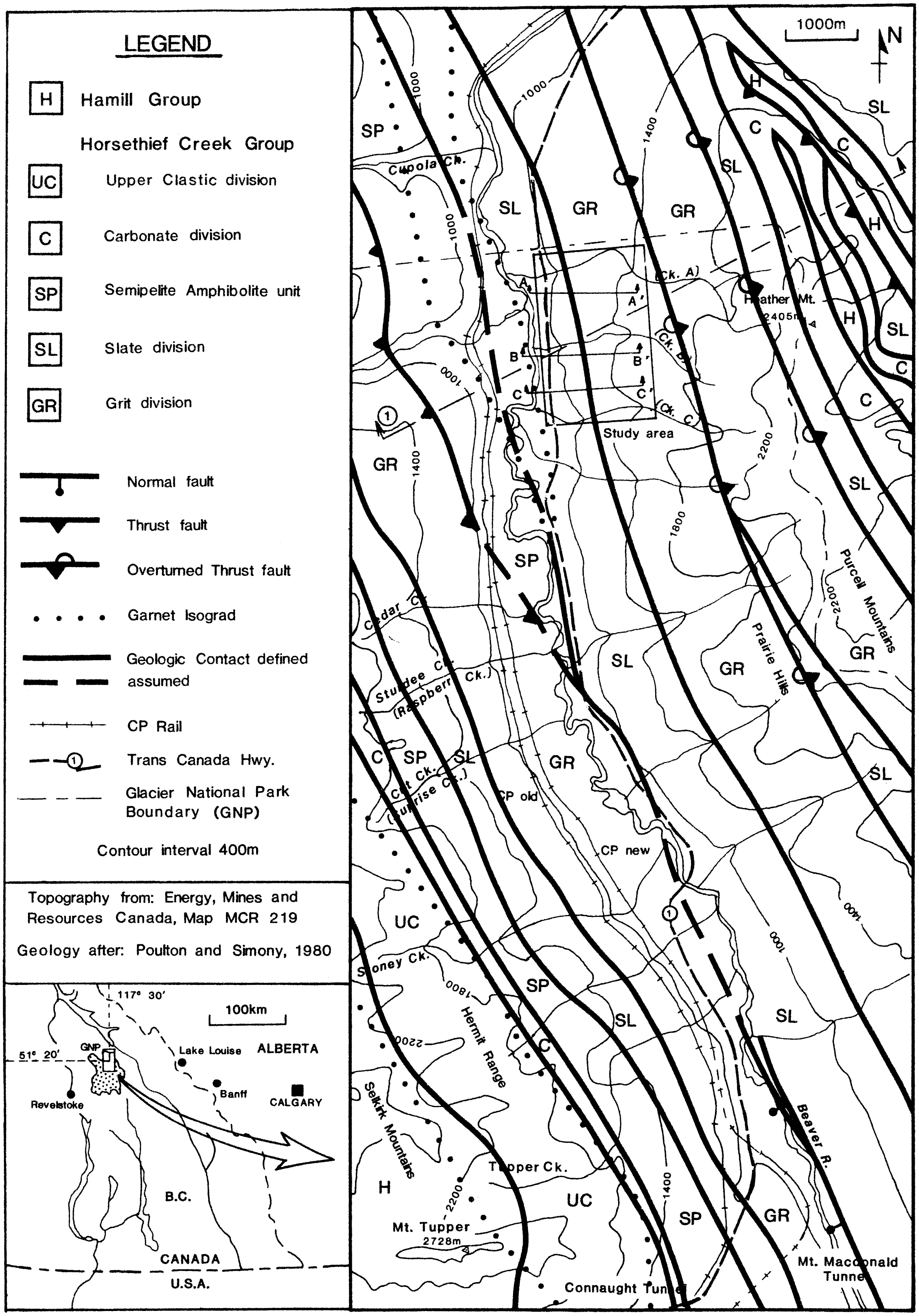

FIG. 2. Regional geology of the Beaver Valley (after Poulton and Simony 1980).

Ltd. 1976; Thurber Consultants Ltd. 1979*a*). The distribution of landslides was first studied in 1976 as part of the geotechnical evaluation of routes for the Rogers Pass grade revision project. Evidence of toppling was found during detailed geotechnical investigations (Piteau and Associates Ltd. 1982; Thurber Consultants Ltd. 1979*b*). Pritchard *et al.*

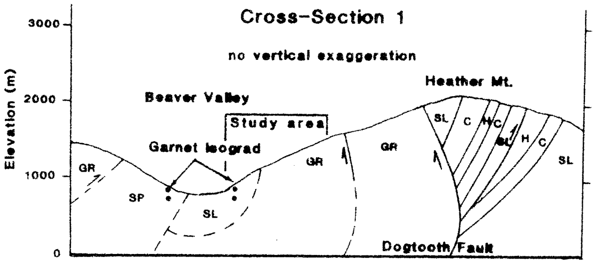

FIG. 3. Geological cross section number 1, Beaver Valley (see Fig. 2 for legend; after Simony and Wind 1970 and Poulton and Simony 1980).

(1988) showed the distribution of landslides and speculated that they represented the limiting condition of a toppling process.

Geological setting

The Beaver Valley is flanked on the east by the Prairie Hills of the Purcell Mountains and on the west by the Hermit Range of the Selkirk Mountains (Fig. 2). The valley is formed in low grade metasedimentary rocks belonging to two groups: the Hadrynian (Late Precambrian) Horsethief Creek Group and the Lower Cambrian Hamill Group (Wheeler 1963; Simony and Wind 1970). The Horsethief Creek Group includes a lower grit division successively overlain by slate, carbonate, and upper clastic divisions. The upper portion of the slate division is locally subdivided into a semipelite amphibolite unit. The Hamill Group is predominantly quartzite (Simony and Wind 1970).

The east slope of the Beaver Valley consists of a series of imbricate thrust sheets, with the slopes formed primarily in the overturned lower grit and slate divisions of the Horsethief Creek Group (Fig. 3). The west slope of the valley is formed in an upright sequence of the grit division, semipelite amphibolite unit, and slate division, and only one west dipping thrust fault is reported. Another is mapped regionally beneath the valley floor near the bottom of the west slope (Poulton and Simony 1980).

The rocks are folded, exhibiting planar (S0) bedding foliation on the scale of outcrop. The S0 foliation trends dominantly northwest, dipping steeply east on the east side of the valley and steeply west on the opposite side (Simony and Wind 1970). Penetrative foliation (S1) that is axial planar to S0 folds is obscured on both sides of the Beaver River by crenulation cleavage (S2) related to a later phase of tectonic deformation (Simony and Wind 1970).

Geomorphic development of the Beaver Valley is dominated by glacial and fluvial processes. The last major glacial event began between 20 000 and 23 000 years B.P. and reached elevations in excess of 2400 m (Fulton 1968; Mylrea 1969). Ice had retreated from the area by 10 000 years B.P. During deglaciation, occasional readvances oversteepened the valley slopes below approximately 1100 m elevation. Slope angles are between 20 and 25° above this elevation, but steepen to between 30 and 45° below it. Thin gravelly tills and stratified sands and gravels were deposited on valley slopes during the last glaciation.

Drainage of the Beaver Valley was blocked by at least one later glacial advance down the Cupola Creek Valley (Fig. 1). This blockage formed a lake marked by raised deltas at approximately 990 m elevation at the mouths of major tributary streams (Thurber Consultants Ltd. 1983*a*). These deltas have been reworked and deposited as alluvial fans across the valley floor. The reworked sediment, together with sediment transported by major tributary streams, has caused the fans to prograde across the Beaver Valley, creating several local base levels behind which the floodplain of Beaver River has aggraded.

Characteristics of mass movements

Landslides in the Beaver Valley are classified as rock slumps and rock slides (Varnes 1978). Comparison of Figs. 1 and 2 shows that most landslides are on the lower valley slopes in the lower grit and slate divisions, including the semipelite amphibolite unit, but also extend into the lower grit division of the Horsethief Creek Group. The lower grit division consists mainly of fine- to coarse-grained, gritty, feldspathic and micaceous sandstone with slate interbeds (Simony and Wind 1970); planar bedding and graded beds are common (Poulton and Simony 1980). The semipelite amphibolite unit consists of platy quartzo-feldspathic pelitic rocks interbedded with finer grained pelites and containing sheets of amphibolite ranging up to a few metres thick. The remainder of the slate division consists of pelitic rocks, with minor coarser clastic and carbonate interbeds (Poulton and Simony 1980).

The headscarps of the landslides are 450–1250 m above the Beaver River floodplain, which is at approximately 825 m elevation. The estimated volumes of the landslides range from 1 to 30 million cubic metres. Glacial erosion beneath the present valley floor extends below 755 m elevation (Thurber Consultants Ltd. 1983*b*). As the landslides probably extend below the current floodplain level, these estimates of relief and volume are minima.

The ages of the landslides are unknown. All show evidence of post-glacial movement; however, interbedding of landslide and moraine deposits at the Griffith slide (Fig. 1) indicates that the initial development of this slide predates the last glaciation. Relatively recent progressive deformations at the Griffith slide have displaced the CP Rail grade (Thurber Consultants Ltd. 1979*a*). Whether other landslides are moving, and their rate of movement, are not known.

Results of field studies

An area of the east slope of the Beaver Valley was selected for detailed study. It includes the deep-seated Heather Hill landslide and slopes immediately north that show varying degrees of toppling, but no apparent deep-seated failure (Figs. 4, and 5). Three creeks are deeply incised into the slope, providing natural exposures of rock below the topographic surface of the main valley slope.

Fieldwork during the summer of 1988 included controlled structural mapping traverses along the creek gullies, the scarp of the Heather Hill landslide, and the highway back slope (Pritchard 1989).

Local geology

The lower grit and slate divisions of the Horsethief Creek Group (Fig. 2) in the study area consist of quartz biotite schist belonging to the slate division at the base of the slope, changing upslope to a section in which feldspathic grit of the lower grit division predominates. Bedding thickness ranges from millimetres to tens of metres but is commonly