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Movement of King's Throne Rock Glacier, Mount Rae Area, Canadian Rocky Mountains

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ABSTRACT

This paper reports on the results of an eight-year geodetic survey at King's Throne rock glacier in the Front Ranges of the southern Canadian Rocky Mountains. The rock glacier originates below talus deposits skirting towering bedrock walls. It has many of the geomorphological characteristics of an active rock glacier, with photographic evidence collected over an 18-year period (1978–96) attesting to this activity. The positions of 25 survey markers on the rock glacier surface were established by triangulation surveys in 1988. Repeat surveys are used to describe surface movements over a one-year and an eight-year period. Between 1988 and 1996, horizontal displacements of the largest set of boulder targets averaged 5.35 ± 0.39 cm a^{-1} and were accompanied by vertical displacements averaging 2.49 ± 0.62 cm a^{-1}. Two groups of smaller boulders moved some 27% faster and may reflect the influence of ancillary transport processes. These measurements are interpreted to show that King's Throne rock glacier is advancing downslope at an average rate of 1.61 cm a^{-1}. This rate of rock glacier mass movement is lower than those previously reported from the Canadian Rocky Mountains but is comparable to rates at other North American sites. Our survey results confirm that King's Throne rock glacier is presently active but suggest that it may be thermally unstable and adjusting to present-day climates. Copyright © 1999 John Wiley & Sons, Ltd.

RÉSUMÉ

Le présent article donne les résultats de 8 années de levés géodésiques réalisés sur le glacier rocheux King's Throne, dans les Front Ranges (Montagnes Rocheuses canadiennes méridionales). Ce glacier rocheux débute sous des dépôts d'éboulis contournant des tours de roche en place. Il présente de nombreuses caractéristiques géomorphologiques propres aux glaciers rocheux actifs avec d'ailleurs des preuves photographiques de mouvements au cours d'une période de 18 ans (1978–1996). Les positions de 25 repères à la surface du glacier rocheux ont été établies par triangulation en 1988. Des levés répétés ont permis de décrire les mouvements de surface pendant 8 ans. Entre 1988 et 1996, les déplacements horizontaux du plus grand nombre de repères inscrits sur des gros blocs ont été en moyenne de $5{,}35 \pm 0{,}39$ cm a^{-1} et ont été accompagnés par des déplacements verticaux ayant en moyenne une valeur de $2{,}49 \pm 0{,}62$ cm a^{-1}. Deux groupes de plus petits blocs se sont déplacés environ 27% plus vite et reflètent sans doute l'influence de mouvements secondaires. Ces mesures montrent que le glacier rocheux de King's Throne s'avance selon la pente à une vitesse moyenne de 1,61 cm a^{-1}. Cette

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vitesse de progression est plus faible que celles qui ont été décrites dans les Montagnes Rocheuses canadiennes mais est comparable à des vitesses observées en d'autres endroits d'Amérique du Nord. Nos résultats confirment que le glacier rocheux dénommé King's Throne est maintenant actif, mais suggère qu'il peut être thermiquement instable et s'ajusterait au climat actuel. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: rock glaciers; Canadian Rocky Mountains; mass wasting

INTRODUCTION

Rock glaciers are a prominent geomorphic element of the Canadian Rocky Mountains (Luckman, 1981). The majority of these rock glaciers are characterized as lobate- or tongue-shaped masses or poorly sorted angular debris extending down valley from the base of cliffs or cirques (Ommanney, 1976). Spatial variations in the distribution of rock glaciers are evident in the Canadian Rockies, as the altitudinal belt of rock glacier deposits varies latitudinally from 2250 to 2500 m ASL in the vicinity of southern Banff National Park (lat. 50°N) (Papertezian, 1973; Smith, 1979) to 1890 to 2670 m ASL in Jasper National Park (lat. 53°N) (Luckman and Crockett, 1978). The southern extent of rock glacier deposits in the Canadian Rockies remains unknown, although increased aridity and a general lowering of the landscape south of 50°N latitude must restrict their occurrence.

Rock glaciers in the Canadian Rockies are polygenetic in origin, having been derived from rockfall (Yarnal, 1979; 1982; Bajewsky, 1988), rockslide (Gardner, 1978; McAffee, 1995; McAffee and Cruden, 1996) and/or glacial deposits (Osborn, 1975). While many are thought to consist of a mixture of rock debris and ice (Yarnal, 1979; Bajewsky, 1988), a few contain cores of glacial ice buried by surface debris (Gardner, 1978). As is the case in many studies of rock glacier morphodynamics (Martin and Whalley, 1987), research from the region indicates their evolution is geomorphologically complex and perhaps linked to changing climatic regimes (Yarnal, 1982).

Only a few detailed rock glacier site studies have been carried out in the Canadian Rockies. Rock glaciers overrunning a Little Ice Age moraine at Lake Louise in Banff National Park, Alberta were examined by Osborn (1975) and determined to be advancing between 30 and 60 cm a^{-1}. Yarnal (1979; 1982) described surface debris fabrics on a rock glacier in Mount Assiniboine Provincial Park, British Columbia and attributed them to creep, variable sediment sources, sifting processes and time. Gardner and Bajewsky (1987), Bajewsky (1988) and Bajewsky and Gardner (1989) report on the role rock glaciers play in the transport of dissolved and suspended stream loads at Hilda rock glacier in northern Banff National Park, Alberta.

Although rock glaciers are recognized as an important alpine mass wasting phenomenon within the region (Luckman, 1981; Gardner *et al.*, 1983), the only insight into rock glacier rates of activity comes from an analysis of photographs showing the historic positions of three rock glaciers at Lake Louise, Alberta between AD 1902 and 1974 (Osborn, 1975). No measurements of contemporary rock glacier activity exist from the Canadian Rockies that document either surface flow rates or the rate of present-day rock glacier mass wasting. This paper reports on the results of an eight-year geodetic survey of rock glacier activity at a single site in the Front Ranges of the southern Canadian Rockies.

FIELD AREA

The rock glacier examined in this study is one of 19 identified in the Mount Rae area of south-western Alberta (Smith, 1979). The Mount Rae area is a 100 km^2 segment of high alpine country located along the south-eastern border of Peter Lougheed Provincial Park (Figure 1). Situated 75 km south-west of Calgary, the area is characterized by deeply sculptured mountains composed of thrust faulted sedimentary strata (Allan and Carr, 1947) and distinctly U-shaped trunk valleys mantled with till, alluvial and colluvial deposits. Radiocarbon evidence from the nearby Elk River valley shows that the most recent phase of valley glaciation in the area was completed by 13,500 BP (Ferguson and Osborn, 1981). Since that time glacial activity has been restricted to cirque locations, where limited Holocene activity has been reported (Jackson, 1980; Lawby *et al.*, 1995;

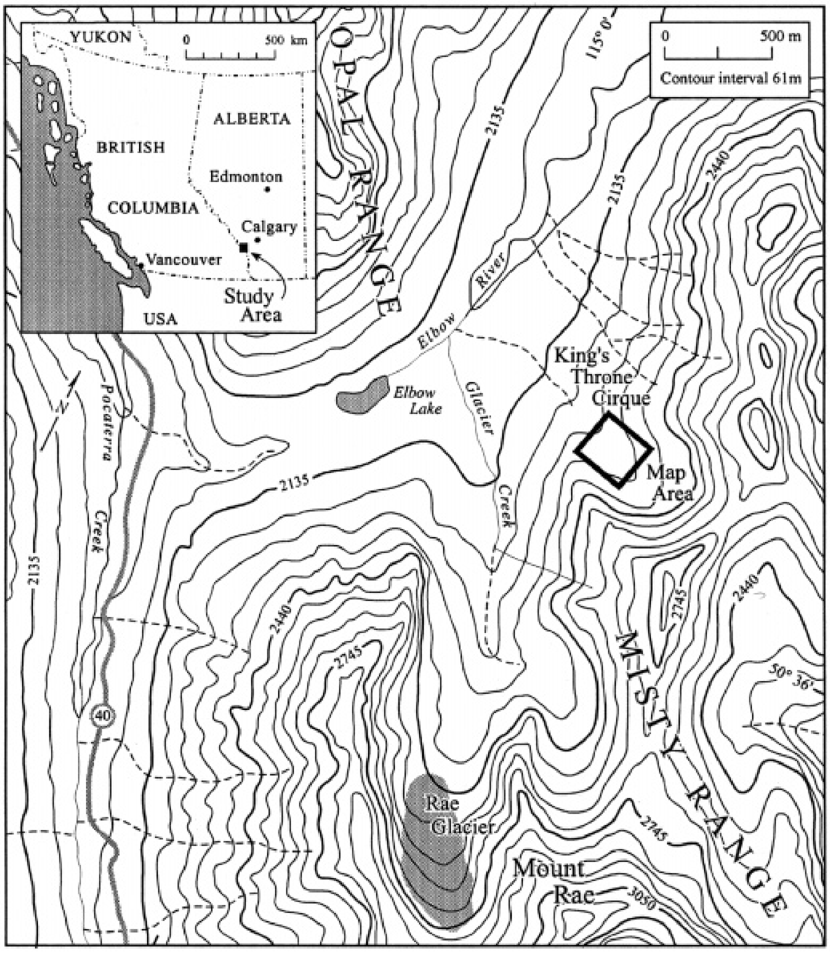

Figure 1 Location map of the study site in the Mount Rae area, southern Canadian Rocky Mountains.

Smith *et al.*, 1995). The Mount Rae area is described in detail by Gardner *et al.* (1983) and has been the focus of continuing geomorphic investigations (1974 to the present) designed to provide a quantitative perspective on sediment transfer rates and magnitudes (Gardner, 1983; Smith, 1992).

Almost all of the rock glaciers found in the Mount Rae area are located at the foot of talus slopes below weathering free faces. The majority are found within a narrow altitudinal band (2250 to 2440 m ASL) and are composed of blocky limestone and dolomite detritus from the Rundle Group or Exshaw and Banff Formations (MacQueen and Bamber, 1968). While the most common forms are recognized as 'protalus' rock glaciers (Whalley and Martin, 1992), there are a few examples of large valley-floor rock glaciers. The morphology of all of these rock glaciers, their presence below highly fractured free faces, and the large calibre of debris which characterizes their surfaces, are consistent with an origin related to high-magnitude rockfalls of likely paraglacial origin (e.g. Gardner, 1977; Luckman and Fiske, 1997). Limited excavations at several sites in the area suggest the majority are of non-glacial or ice-cemented origin and, if active, probably move as a result of some form of permafrost creep (e.g. Haeberli, 1985).

Permafrost conditions have been documented within blocky deposits in this region (e.g. Harris and Pederson, 1998) and were confirmed within the Mount Rae area by Smith (1979) who recorded the persistence of ground temperatures below 0 °C on a west-facing ridge crest at 2431 m ASL. Active periglacial processes in the area include those

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Figure 2 View south-eastward of King's Throne rock glacier showing steep frontal embankment and blocky surface appearance of the deposit. Note the distal talus apron which mantles the rock glacier flank and extends onto the surface of the distal ephemeral pond. Adjacent to the three Bighorn Sheep (circled) are fine-sediment deformation lobes extending beyond the talus base. Photograph taken on 16 August 1996.

leading to the development of patterned ground (Smith and Gardner, 1979; Smith, 1987a) and solifluction landforms (Smith, 1987b; 1992).

King's Throne Rock Glacier

Our investigations focused on King's Throne rock glacier (unofficial name), a small lobate-shaped rock glacier located in a north-west-facing cirque in the headwaters of the Elbow River (58°38′N, 114°59′W; Figure 1). The rock glacier trends to the north-west (340–345°), has an overall length of *c*. 175 m, an average width of 97 m (35–133 m) and a surface area of *c*. 12,000 m^2. The rock glacier terminates at 2354 m ASL in a small, ephemeral, moraine-dammed pond.

King's Throne rock glacier originates from talus deposits skirting towering massive to thickly bedded bedrock walls of Mount Head Formation limestone (MacQueen and Bamber, 1968). A slight depression marks the boundary between the steeply sloping talus (35°) and rock glacier debris. While the rock glacier has a relatively consistent surface slope (15°), furrow-like features, centimetres in height and metres in length, trend subvertically along its eastern perimeter.

Excavations into the rock glacier surface show it consists of angular to subangular boulders up to 60 m^3 in size (Figure 2). The surface mantle has an interstitial void ratio exceeding 40% and is very unstable. A lichenometric survey of the rock glacier was undertaken using a locally calibrated *Xanthoria elegans* (Link) Th. Fr. growth curve (McCarthy and Smith, 1995) in an attempt to provide a relative measure of surface stability (cf. Luckman and Fiske, 1995; Whalley *et al*., 1995; Sloan and Dyke, 1998). A lack of lichens on the eastern and central portion of the rock glacier suggest these surfaces are younger or more active than the western perimeter, where lichens approaching 100 years in age were observed.

A 2 m deep pit excavated on the rock glacier surface on 21 July 1989 (see Figure 3 for location) revealed a heterogeneous assemblage of limestone boulders, cobbles, gravels and coarse sands with no

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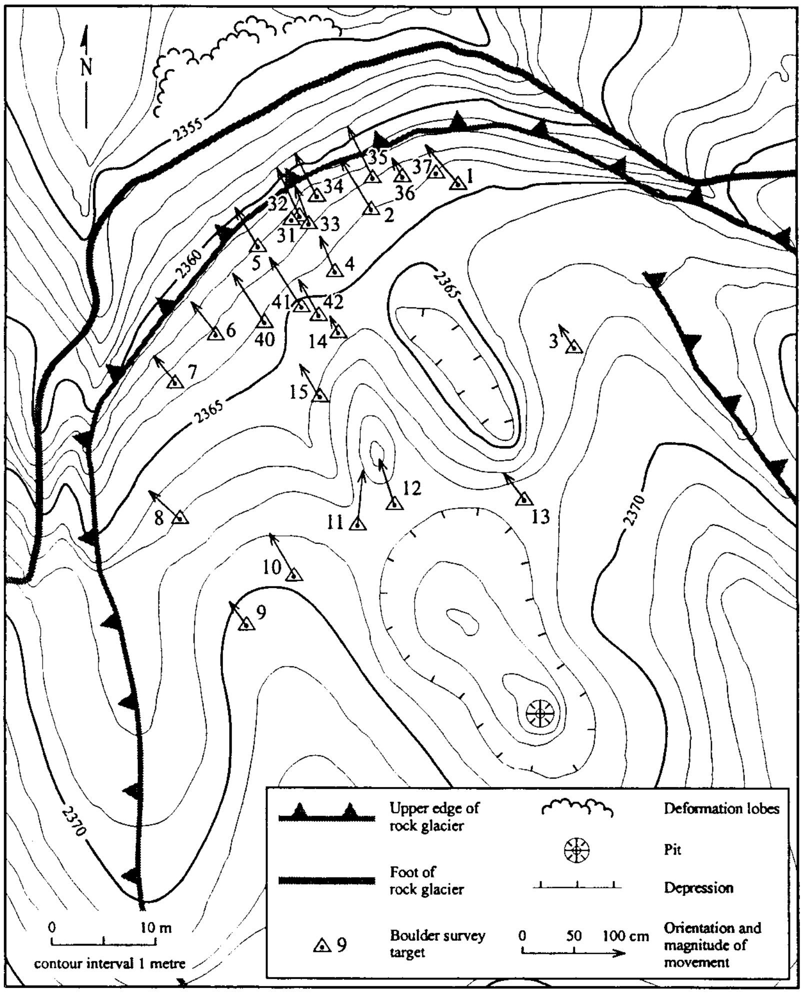

Figure 3 Location of survey markers and topographic character of King's Throne rock glacier. Shown on the map are the direction and relative transport distance for 1988–96.

apparent sorting. Ice-cemented boulders at 1.6 m were removed, exposing a basal ice lens at the bottom of the pit. Water flowed freely across this surface, continuing to do so at least until August 1990. When the pit was re-examined in early September 1991 ice was no longer visible, although flowing water could still be heard a short distance below the pit base.

The steeply sloping (35–40°) 7 m high frontal margin of the rock glacier is unstable and has a 'fresh' light brown-coloured appearance (Figure 2). Comparative oblique photographs (1978–96) emphasize that significant sediment transport occurs down this debris apron (Figure 4). The cascading debris occasionally spills beyond the talus apron and overturned boulders were located with yellowed and dying *X. elegans*.

The rock glacier snout is characterized by coalescing vegetation- and moss-covered fine-sediment lobes which extend beyond the coarse-debris apron (Figure 2). These lobes have a terraced appearance and are composed of layered and deformed pond-floor silty loams. They are interpreted as 'push-lobes' (Shroder, 1987) and are attributed to deformation loading associated with the advance of King's Throne rock glacier (cf. Benedict 1981; 1982).

RESEARCH METHODS

King's Throne cirque was surveyed in 1988 to construct a base map of the rock glacier and surrounding mountain slopes. Permanent

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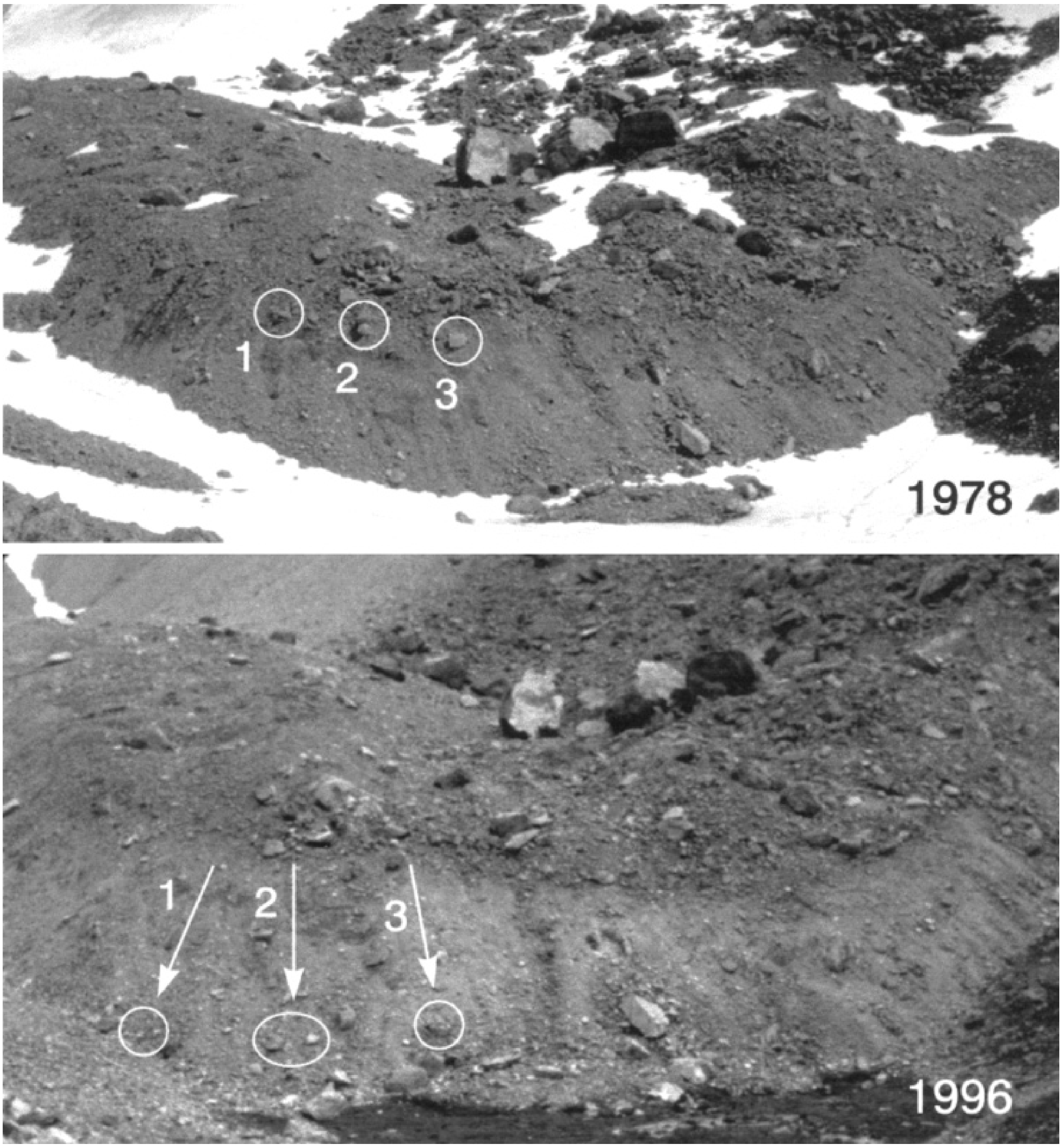

Figure 4 Comparison of north-eastern flank of King's Throne rock glacier in 1978 and 1996. Note the relative movement of the circled boulders which have been transported down the distal apron of the rock glacier. These boulders were not included in the geodetic survey reported within the paper.

benchmarks were established and the positions of survey points marked by triangulation with a Wild T2 (020B) theodolite. Three-dimensional attributes were calculated and contoured to produce a site map using Autocad™ (release 12).

The flow characteristics of rock glaciers dictate the use of geodetic theodolite surveys to observe their activity effectively (Haeberli, 1985; Berthling *et al.*, 1998). In this instance, two fixed survey positions, located in front of and to the west of the

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rock glacier terminus, were used to monitor the movement of survey targets along lines transverse to the length of the rock glacier (Figure 3). Twenty-five boulders were marked with small painted targets positioned in the centre of crosses chiselled into the boulder surfaces. Targets 1 to 15 consist of boulders having *a*-axis lengths ranging from 0.5 to over 4 m. These boulders were firmly interlocked with other large boulders and accordingly provide a measure of movement by the entire rock glacier (cf. Haeberli, 1985). Targets 31 to 37 are medium-sized boulders, and targets 41 to 43 are small boulders positioned a few metres back from the rock glacier snout. The latter two groups of boulders rest on the surface of the rock glacier and were targeted as part of a corollary study concerned with debris transport at King's Throne rock glacier (Koning, 1994).

Three separate theodolite surveys were completed in 1988 (June–August) to establish the target coordinates (x, y, z). Four sets of readings were taken during each survey and the coordinates were determined with a programmable Hewlett Packard HP 41CX calculator. The data sets were examined for both precision and error, but no precision errors were encountered. This finding is probably due to the fact that the greatest distance between a target and a fixed station was less than 70 m. Our residual error estimates were in the range of a few millimetres and may be an artifact of rock movement between the June and August surveys. This survey protocol was repeated in August 1989 with a Wild T2 (020B) theodolite and again in August 1996 with a Zeiss (NE-20S) theodolite, to measure surface movements over a one-year and an eight-year period.

RESULTS

King's Throne rock glacier has many of the characteristics of an active rock glacier. These include: a steep sharp-crested front margin with a fresh unstable appearance (Parson, 1987; Dyke, 1990); sparse vegetation and limited lichen growth (Wahrhaftig and Cox, 1959; White, 1971; Benedict, 1981; Dyke, 1990); and an apron of scattered and overturned boulders beyond the debris snout (Wahrhaftig and Cox, 1959; White, 1971; Benedict, 1981; Calkin *et al*., 1987; Parson, 1987). These empirical observations, and photographic evidence of sediment transport down the frontal margin over an 18-year period, attest to the activity of King's Throne rock glacier.

Boulders on the surface of the rock glacier showed marked movement over the observation period (Figure 3). In the initial year of the survey (1988–89), horizontal vector displacements for targets 1–15 averaged 4.61 ± 0.45 cm a^{-1} and a net subsidence equalled 0.80 ± 0.04 cm a^{-1} (Table 1). Over the longer-term survey period (1988 to 1996), total horizontal displacements for targets 1–15 ranged from 29.1 to 59.1 cm (5.35 ± 0.39 cm a^{-1}) and were accompanied by a general surface lowering ranging from 8.1 to 65.5 cm (2.49 ± 0.62 cm a^{-1}) (Table 1). With the notable exception of target 11, all of the large boulders moved to the north-west and followed the general downslope trend of the rock glacier (Figure 3). Nevertheless, a spatial appraisal of the data shows that the targets located within the eastern portion of the rock glacier moved faster (6.03 cm a^{-1}) than those positioned within either the central (5.45 cm a^{-1}) or western (4.86 cm a^{-1}) areas. This observation is supported by our lichenometric measurements which pointed to increased stability along the western perimeter of the rock glacier. While these surface movement rates are relatively slow, they do fall within the range of rates reported at other North American sites (White, 1971; Potter, 1972; Johnson and Nickling, 1979; Jackson and MacDonald, 1980; Blumstengel and Harris, 1988; Dyke, 1990; Sloan, 1998; Sloan and Dyke, 1998).

The two groups of smaller boulders (targets 31–37 and 41–42) moved some 27% faster than the large boulders (targets 1–15). Total horizontal displacements (1988 to 1996) within this group of targets ranged from 46.3 to 60.5 cm (6.81 ± 0.39 cm a^{-1}) and were accompanied by total lowering ranging from 11.2 to 120.1 cm (3.96 ± 0.39 cm a^{-1}) (Table 1). The higher rates of activity described by these targets may reflect the influence of ancillary transport processes (e.g. snow avalanching) and a mechanism whereby sifting and crude sorting processes might be hastened on the rock glacier surface (Yarnal, 1979; 1982).

Subsidence of a rock glacier surface can be interpreted as an outcome of rock glacier sliding or thaw settlement or as related to underlying changes in elevation (Calkin *et al*., 1987; Barsch, 1996). Most of the surface lowering recorded at King's Throne rock glacier occurred at targets adjacent to the steep frontal flanks of the rock glacier (e.g. target 41, Figure 3). In these instances, the rate of horizontal transport was almost twice the rate of lowering (Table 1). Significant lowering of the rock glacier surface did occur at a few individual high

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Table 1 Movement of survey targets at King's Throne rock glacier, 1988–89 and 1988–96.

Target no.	Horizontal movement			Vertical movement		
	1988–89	1988–96		1988–89	1988–96	
	Total movement (cm)	Total movement (cm)	Average movement (cm a^{-1})	Net lowering (cm)	Net lowering (cm)	Average subsidence (cm a^{-1})
1	5.4	53.3	6.7	0.9	23.9	3.0
2	6.0	56.8	7.1	0.7	19.4	2.4
3	6.4	34.4	4.3	0.1	8.1	1.0
4	4.0	41.3	5.2	0.6	15.8	2.0
5	5.0	43.2	5.4	0.9	20.7	2.6
6	3.8	38.9	4.9	0.8	19.2	2.4
7	2.4	36.9	4.6	0.7	14.4	1.8
8	0.9	40.3	5.0	0.7	17.8	2.2
9	2.9	31.6	4.0	0.5	10.1	1.3
10	4.9	46.6	5.8	0.5	65.5	8.2
11	3.8	59.1	7.4	0.6	23.7	3.0
12	5.4	50.0	6.3	0.5	14.8	1.9
13	10.8	29.1	3.6	0.4	12.2	1.5
14	5.1	39.3	4.9	0.5	14.5	1.8
15	2.4	41.0	5.1	0.6	17.5	2.2
Mean 1–15	4.61	42.79	5.35	0.6	19.84	2.49
31	4.0	missing	missing	0.6	missing	missing
32	3.2	50.0	6.3	0.5	26.6	3.3
33	7.3	54.1	6.8	0.5	25.2	3.2
34	7.6	51.0	6.4	0.5	21.2	2.7
35	6.9	52.4	6.6	0.3	11.5	1.4
36	7.4	59.8	7.5	0.3	14.3	1.8
37	8.4	missing	missing	0.3	missing	missing
40	7.1	60.0	7.5	0.5	23.1	2.9
41	8.0	60.5	7.6	1.0	120.1	15.0
42	8.1	46.3	5.8	0.2	11.2	1.4
Mean 31–42	6.5	54.26	6.81	0.47	31.65	3.96
Overall mean	5.6	48.9	5.6	0.55	24	3

points (e.g. target 10, Table 1) in the vicinity of longitudinal furrows on the rock glacier surface where flowing water was heard (Figure 3). Water issuing from the rock glacier snout drains from persistent outlets and retains a uniform temperature of 0 °C through the ablation season (Koning, 1994). These observations suggest that the frozen core of King's Throne rock glacier is strongly influenced by channelized subterranean stream flows which appear to have initiated differential thermal erosion.

DISCUSSION

Like many other rock glaciers in this region, King's Throne rock glacier probably originated as blocky rockfall debris (Gardner, 1983). Observations of dirty snow and debris avalanches, frequent low-magnitude rockfalls (134 rockfalls over 257 hours of observation, 1988 and 1989) and seasonally cool temperatures at the site (Koning, 1994) suggest the rock glacier may have gradually developed an ice-cemented permafrost core (e.g. Evin, 1987). Nevertheless, these processes must have been far more efficient at some earlier time in the Holocene (e.g. Luckman and Fiske, 1995; 1997). Boulder traps monitored on the rock glacier surface from 1988 to 1989 illustrate that rockfalls and snow avalanches are presently adding less than 1600 kg a^{-1} of debris to the rock glacier (Koning, 1994).

The present-day activity of King's Throne rock glacier is manifest by several morphological

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characteristics, a scanty lichen cover, photographic evidence and the measurement of surface movement by triangulation surveying. Nevertheless, except for the discovery of an ice-cemented horizon within 2 m of the rock glacier surface, we have little direct appreciation for its rheological characteristics. Whalley and Azizi (1994) and Barsch (1996) have suggested, however, that even if the internal composition of a rock glacier is unknown, the associated basal shear stress τ inducing deformation can still be calculated. Following Barsch (1996, p. 175):

$$\tau = \delta\, z\, g \sin \alpha$$

where δ is density (1.8 g cm^{-3}), z is depth (6.76 m to 10.0 m), g is acceleration due to gravity and α is surface slope (15°). Using this formula, we estimate that King's Throne rock glacier has a basal shear stress of *c.* 30 to 45 kPa. While this value is much lower than those calculated for a number of active rock glaciers by Haeberli (1985) and Barsch (1996), it does fall within the range (20–40 kPa) that Wagner (1992, p. 161) reported for the Murtèl rock glacier. Thus, our findings support the contention of Barsch (1996) that the basal shear stresses required to induce rock glacier flow may be far smaller than hitherto assumed.

Several authors have shown that the height of the talus apron can provide insight into which components of flow are operating at a particular rock glacier (Wahrhaftig and Cox, 1959; Haeberli, 1985; Barsch, 1996). At King's Throne rock glacier, the apex of the talus apron appears as an abrupt break at *c.* 0.7 times the height of the front slope (Figure 2). Given this observation, the activity at this site appears to be transitional between that expected for the movement of a thin surface layer over a stable interior (Wahrhaftig and Cox, 1959, p. 398) and that generated where the surface layer was carried by a mobile interior (Johnson and Nickling, 1979, pp. 2279–82; Barsch, 1996, pp. 169–70).

Barsch (1996) has also noted that evaluation of the height of the talus apron with respect to average surface velocity provides a means to describe the mass movement of the entire rock glacier. Following Barsch (1996, p. 171), the average velocity V_m of King's Throne rock glacier can be calculated as:

$$V_m = (1 - h_m)\bar{V}_s$$

where $\bar{V}_s$ is the mean surface velocity parallel to the slope and h_m is the ratio of the talus height to the height of the front slope. At King's Throne rock glacier then, where $h_m = 0.7$ and $\bar{V}_s = 5.35$ cm a^{-1}, these calculations suggest the entire rock glacier moved forward at a rate of 1.61 cm a^{-1} between 1988 and 1996. This rate of mass transport is considerably lower than that described by Osborn (1975) in the only previous study of rock glacier dynamics in the Canadian Rocky Mountains. Given this slow rate of displacement and the maximum distance travelled (*c.* 175 m), King's Throne rock glacier may be a paraglacial deposit that has remained active through the Holocene.

CONCLUSIONS

The results of our field surveys in 1989 and 1996 at King's Throne rock glacier showed that all of the boulders marked and surveyed on the rock glacier surface in 1988 were being transported downslope. Mass wasting of the largest set of boulder targets shows that horizontal surface displacements were equal to 5.35 ± 0.39 cm a^{-1} and were accompanied by vertical displacements of 2.49 ± 0.62 cm a^{-1}. These measured rates of surface activity demonstrate that King's Throne rock glacier is presently active and are interpreted to show it is advancing downslope at an average rate of 1.61 cm a^{-1}.

As anticipated from our photographic and lichenometric records, surface movements were fastest along the eastern surface of the rock glacier and at the rock glacier front where debris spills down onto the fringing talus apron. The fact that all of our measurements and observations show that King's Throne rock glacier is active, adds additional support to the contention that rock glacier creep may be occurring at lower basal shear stress values than is generally assumed.

Depressions and furrows on the rock glacier surface are identified with subterranean water flows. Taken in concert with a general lowering of the rock glacier surface, these thermokarst features suggest that King's Throne rock glacier may be adjusting to ameliorating climates initiated at the close of the Little Ice Age in this area (Wig and Smith, 1994). Surveys by McCarthy and Smith (1994) have shown that glaciers within this region have lost between 15% and 80% of their area in the last 75 years and may be smaller now than they have been at any time in the last 3000 years (Luckman, 1998). Given that investigations at nearby Rae Glacier (Figure 1) revealed a

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cumulative volumetric loss of glacier ice equalling 76% between 1881 and 1991 (Lawby *et al.*, 1995), it may be that King's Throne rock glacier is thermally unstable and adjusting to the present-day climates.

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