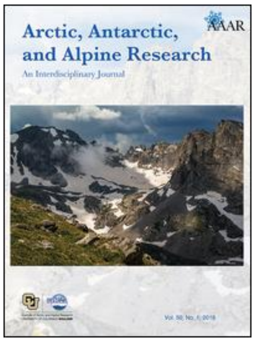

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THE PHYSIOGRAPHY OF THE CASTLEGUARD KARST AND COLUMBIA ICEFIELDS AREA, ALBERTA, CANADA*

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ABSTRACT

The Columbia Icefields are highland ice caps developed upon benchlands of massive platform carbonates in the Main Ranges, Rocky Mountains. Ice is discharged via major valley glaciers, including South Glacier, Castleguard Valley. The karst is developed along the southeast edge of the central icefield, extends beneath it, and drains to springs in Castleguard Valley. Altitudinal range of the karst is 1600 to 2600 m a.s.l. Mean annual temperature is estimated to range from 0 to -7°C over this range. Treeline is at ca. 2100 m.

All cirques and valleys were occupied by ice during the late Wisconsinan Glaciation. Modern glaciers are ca. 100 to 300 m in thickness and are receding from well-marked Neoglacial moraines. Periglacial features are prominent on high carbonate surfaces that escaped Neoglacial cover. The principal surface karst features are (1) subglacial precipitates found on newly exposed Neoglacial surfaces; (2) varieties of sinkholes seen on all exposed carbonates above 2000 m; (3) families of springs, most below 2000 m. Castleguard Cave is a major relict system.

The first interpretations of the karst, using simple morphological evidences alone, supposed that the Cave was drained by glacial entrenchment during the Wisconsinan Glaciation. Two modern groundwater caves developed beneath it.

INTRODUCTION

This paper summarizes the physical geography of the Castleguard karst and its environs, as background information for the systematic analyses that follow it in this Symposium. The regional topography is shown in Figure 1. The karst is developed upon a limestone benchland abutting the eastern side of the Columbia Icefield and extending beneath it. Castleguard Mountain (52°06′30″N, 117°15′10″W; elevation, 3083 m a.s.l.) is approximately at its center (Figure 2).

The area is part of the Main Ranges structural province of the Rocky Mountains. Resistant Lower Paleozoic formations are repeatedly overthrust from the west onto resistant Upper Paleozoic formations. The combination has produced massive structures with comparatively little prominent folding or other local deformation. Peaks rise to 3400 to 3700 m and extensive highland plateaus occur on the strongest rocks. Regional trunk valleys (e.g., Sunwapta Pass) follow the overthrust faults and are floored below 1500 m a.s.l. Local relief thus exceeds 2000 m; this is exceptional in the southern Rocky Mountains of Canada, where mean local relief is 1430 m (Ford et al., 1981).

The high plateaus support a chain of highland icecaps. Columbia Icefield is the most extensive of these; it com-

*A version of this paper was presented orally at a symposium, "Karst and Caves of Castleguard Mountain," at the 8th International Congress of Speleology, Bowling Green, Kentucky, U.S.A., 20 July 1981.

prises a central mass (the "central icefield"), plus wings trending west and northwest. It aggregates 325 km² and ranges 2400 to 3450 m in elevation. The central icefield is drained by four major valley glaciers, Athabasca, Saskatchewan, "South,"[1] and Columbia. The two former are easily accessible from the Icefields Parkway (Figure 1) and have received most study (Meier, 1960; Paterson, 1971, etc.). The central icefield, South and Columbia glaciers are remote and heavily crevassed in places, and so they have received no detailed glaciological investigations. All four effluent glaciers occupy deep glacial troughs. That of the South Glacier–Castleguard River (termed "Castleguard Valley") is of most importance here. It is a typical deep U-form feature extending 9 km southeast

[1]"South Glacier" is not an officially recognized name. It is grouped with smaller, high ice bodies surrounding Castleguard Mountain, as "Castleguard Glaciers" on official maps. However, like the Columbia Glacier, etc., it is a major, topographically distinct, effluent of the icefield and so will be specifically named in this symposium.

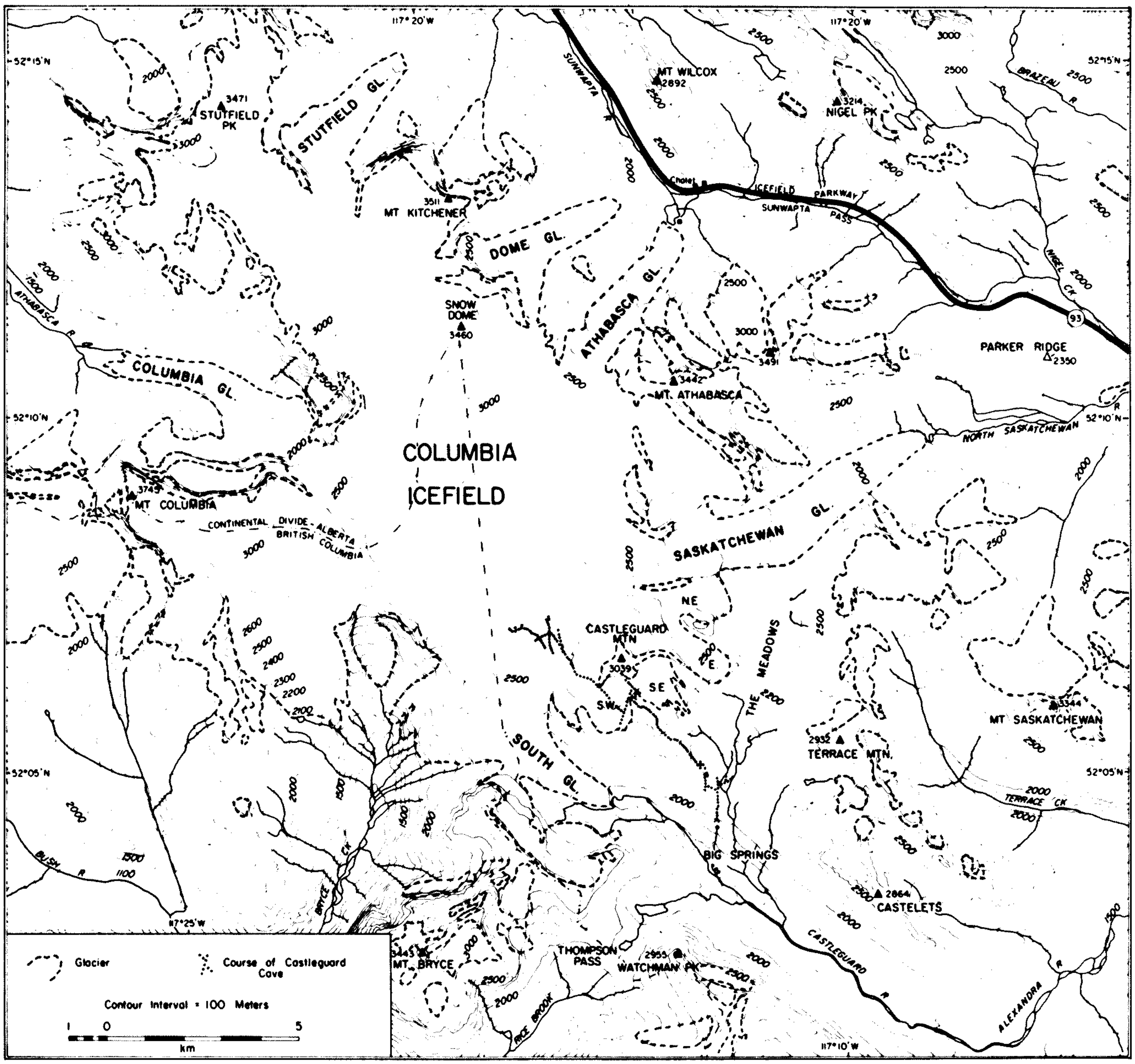

FIGURE 1. Topographic map of the Columbia Icefield and Castleguard karst area, Alberta. Distribution of modern glaciers and the course of Castleguard Cave are shown.

from South Glacier to a concordant junction with Alexandra River at 1550 m a.s.l.

Castleguard Mountain is an isolated, residual alpine horn peak composed of comparatively weak sandstones, shales, and dolomites (Figure 3). It rests upon a massive, terraced plinth of carbonate rocks which rise to 2500 to 2600 m. It is almost completely surrounded by an array of small but coalescent cirque glaciers, which are named for compass points in Figure 1. These rest upon the upper carbonates.

Castleguard Meadows is a broad, comparatively shallow, transection glacier valley hanging above the Saskatchewan and Castleguard valleys at its two ends. Neoglacial lateral moraines of the Saskatchewan Glacier lap on its north end at 2200 m. In the south, it terminates abruptly at 2020 m in the flank of Castleguard Valley, with a hang of 300 m. The east side of the Meadows is enclosed by a chain of arête and horn peaks with small cirque glaciers, the Terrace Mountain range. The Meadows floor may be divided into three parts. The northern third is a glacial benchland with karst sinkholes, plus a few morainic hills rising 20 to 30 m. It is known as "the Col Karst." The central third is a complex of eroded moraine ridges rising 50 to 100 m, with sinkholes or channelled streams where bedrock is exposed on their flanks. The southern third is a flat alluviated by melt streams from the southerly Terrace and southeastern Castleguard glaciers. The streams combine to form "Meadows Creek," which promptly descends the hanging front into Castleguard Valley via a deep canyon.

VEGETATION AND CLIMATE

There is a dense, continuous stand of boreal forest in the Castleguard Valley, extending up to the southern edge of the Meadows at 2050 m. Above this, scattered stands of mature timber are found on thicker soil patches with southerly exposure, to ca. 2100 m. They are interspersed with lush grass and dwarf tree tundra to create an attrac-

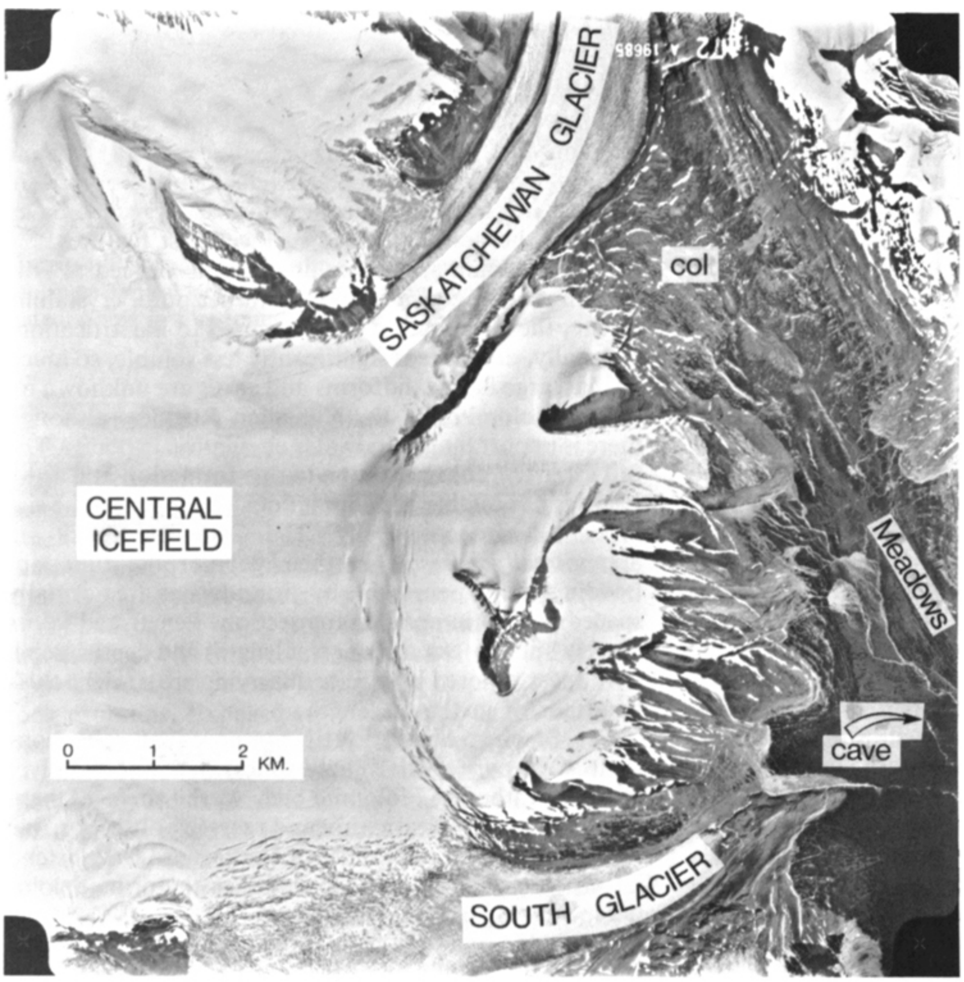

FIGURE 2. Air photo showing the central icefield, Castleguard Mountain, and Castleguard Meadows. (Dept. of Energy, Mines and Resources, Canada; Line A 19685, Photo 172.)

tive parkland in the southern Meadows. Stunted trees extend to 2150 to 2200 m in south-facing positions. Above 2100 m, the tundra is of short grasses with heather and alpine flowers, and much bare ground. The general upper limit of extensive vegetational cover lies at 2300 m.

There are no meteorological stations in the vicinity with long-term data. Ford et al. (1976: 224) calculated mean annual temperatures by a multiple linear regression analysis of data from 74 stations within a 280-km radius. A lapse rate of 1°C per 120 m was obtained. Mean annual temperature is estimated to be 0 ± 0.6°C at 1600 m a.s.l., the approximate base of the karst, falling to -7 ± 0.6°C at 2500 m, where the highest ice-free karst rocks are exposed. Daytime temperatures higher than 0°C are expected throughout the period late March to mid-November. Freezing temperatures may occur at night throughout the summer above 2000 m. Winter snow accumulation begins in October, and snowmelt runoff generally commences in May (Figure 4).

Estimating mean annual precipitation is even more difficult, for the standard reasons encountered in mountains. We believe that it falls in the range of 700 to 1000 mm water equivalent. The mean annual firn line on the icefield probably fell between 2500 and 2700 m during most years of the period 1967 to 1981.

FIGURE 3. The earliest photograph of the Castleguard area. This picture is one of a series taken by Alberta/British Columbia Boundary Commission surveyors in 1918, from a position on the summit of Watchman Peak. Castleguard Mountain is at center-left, with the icefield and Snow Dome rising behind it. Castleguard Valley is in the foreground. Glaciers of Castleguard Mountain extend to the Neoglacial limits. South Glacier, at left, has receded 500 m from its limit. (National Air Photo Library, Canada; P.A.R.C. Box 1024, Print 199.W.1918.)

LITHOLOGY AND GEOLOGIC STRUCTURE

The relevant lithology and structure is summarized in Figure 5. The geological mapping is extended beneath the Castleguard Mountain glaciers and parts of the central icefield. This is derived from our field observations and extrapolations fitted to a contour map of the base of the ice that has been calculated by C. C. Smart (1983, this symposium).

The karst is developed in a platform carbonate sequence of Middle Cambrian age that is mapped by the Geological Survey of Canada in four distinct formations (Douglas et al., 1970). The aggregate thickness in the Castleguard locality is at least 560 m. The base of the sequence is unseen, lying below the floor of Castleguard Valley; i.e., the potential karst base of erosion lies below local surface base levels of erosion today. At the type section (Aitken, 1968) the basal formation, the Cathedral Formation, is 60 m thicker than we can observe here.

For geomorphic and hydrogeologic purposes, the Cathedral Formation at Castleguard should be divided into two members, "main" and "upper" (Figure 5). The main member is a very uniform, well-bedded, massive black crystalline limestone where exposed in the Castleguard Valley. At the north end of the Meadows it displays large, reef-like, patch dolomitization. The main member contains the bulk of the groundwater channels that are active today.

The upper member is again well bedded and massive, but successive beds differ markedly. They include pelletoidal, ruditic, and oolitic beds, and one prominent porcellanous bed. There is strong dolomitic mottling of some of the calcirudites, giving them a distinctive leopardskin appearance. The upper member hosts Castleguard Cave, and also the best-developed surface karst features.

Both the main and upper units of the Cathedral Formation may be considered to be rather pure, crystalline calcite, the carbonate rock best suited to karstification. Normally, dolomite is significantly less soluble, so much so that large karst landforms and caves are unknown on regular dolomites in the Canadian Rockies, although there is important groundwater circulation in places. The full extent of dolomitization in this formation at Castleguard is not established, but it does not appear to be significant hydrogeologically. The Cathedral rocks are *exceptionally massive* in their geomorphic function. Bedding planes penetrable by groundwater are normally spaced 3 to 25 m apart in the section. Penetrated joints are few but may extend for great lengths and depths; some joint faces exposed by glacier quarrying are straight cliffs hundreds of meters in length.

The Stephen Formation is composed of calcareous shale with pyrite, shaly limestones, and one massive, orange-weathering, dolomite bed. At the surface, these strata are rubbly weathering and recessive. It is possible that the headward extremities of Castleguard Cave extend into the Stephen Formation as far as the orange dolomite, but this is not confirmed.

The Eldon and Pika formations are not differentiated from one another by important geomorphic or hydrogeo-

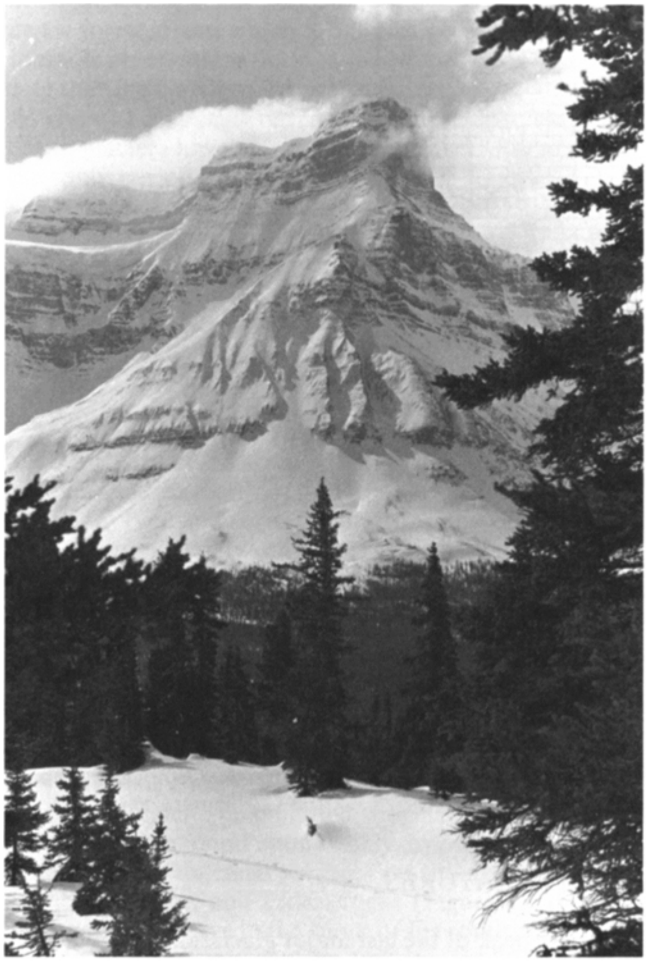

FIGURE 4. Watchman Peak from a point near Castleguard Cave entrance. Typical late winter (April) snow conditions are illustrated. Snow in foreground averages 3 m in depth.

logic characteristics at Castleguard and so may be treated together. They are clearly laminated, intertidal facies, and probably rhythmites. Thin beds of fine-grained, partially dolomitized limestone, of coarser limestone with orange-weathering dolomite partings that protrude on weathering surfaces, and of very fine grained dolomite, succeed one another in the space of a few centimeters up the section. Many beds are strongly rippled. Overridden by ice flow that is nearly normal to the axes of ripple crests, the ripples are dissected into spectacular displays of micro-rock drumlins. Exposed to frost action at the surface, these rocks have decomposed rapidly to platy felsenmeer. Lithologic and frost-weathering habits notwithstanding, these rocks are as massive as the exceptional Cathedral rocks in their response to solutional attack. This is a most unusual phenomenon.

Sedimentary (or neptunian) dikes of resistant sandstone are seen on Pika and Eldon surfaces near the southwest Castleguard glacier (Figure 6). They are vertical and extend for some hundreds of meters before being lost beneath the ice. They are not seen in surface outcrop on the Cathedral or Stephen strata, but do appear at two places in Castleguard Cave. It is possible that these dikes extend downwards through at least 200 m of the section. Their wall contacts with the carbonates may be preferred routes of groundwater penetration.

The Stephen, Eldon, and Pika formations are rather difficult to assess. Their composition is such that in many karst areas they would be expected to function as "aquicludes" (i.e., prohibiting the passage of groundwater because of thei relative insolubility in bulk) or as "aquitards" (i.e., retarding the passage of groundwater). The scale and density of their solutional features is certainly much less than upon the Cathedral rocks. The Stephen Formation forms the floor of the southern Meadows (Figure 5) where it is functioning as an effective aquitard, permitting many streams to collect as Meadows Creek. Elsewhere, groundwaters have been traced passing through the entire Pika–Eldon–Stephen-Upper Cathedral section with astonishing rapidity (C. C. Smart, 1983, this symposium). Nevertheless, it will be argued in the next paper (Ford et al., 1983, this symposium) that strata above the lower Stephen Formation have played an "impermeable caprock" role that is central to understanding the genesis of the older karst.

Directly above the Pika Formation, a thick, purple-maroon shale (the Arctomys Formation) clearly terminates the karst carbonate sequence. It is quite impermeable. It is overlain by several hundred meters of other shales, sandstones, and dolomites of Upper Cambrian-Ordovician age. These are mechanically weak and compose narrow summit masses enclosing glaciers that rest upon the upper carbonates. They supply copious clastic debris.

The karst area is developed on the axis of a broad anticlinal structure plunging southeast. Strata to the north of the Saskatchewan Glacier dip more steeply in northerly directions. Those south of the Castleguard Valley dip south-southwest. Stratal dips on Castleguard Mountain and the Meadows are regularly 5½ to 6½°SSE, and there is a complete absence of the local folding that is common in many platform karst situations. Where Castleguard Cave extends beneath the central icefield, the dip appears to be reduced and strike is not firmly established.

At the Big Springs in Castleguard Valley (Figure 1) a sharp flexure is seen in the Cathedral limestones. They are dipping 35°S. The flexure is a local expression of a hinge line trending northwest-southeast that probably accounts for the position and orientation of the valley. No faulting associated with the flexure is exposed in the valley, but there are small faults with mylonite in Castleguard Cave that indicate lateral displacement. There does not appear to be any vertical displacement that is of hydrogeological significance. The karstified area can be considered as a single, very massive block that is dipping south-southeast into the southeast-oriented Castleguard Valley. Joints are few, but large and deep. Faulting is of little significance. There are a few south-trending sedimentary dikes that are probably long and deep.

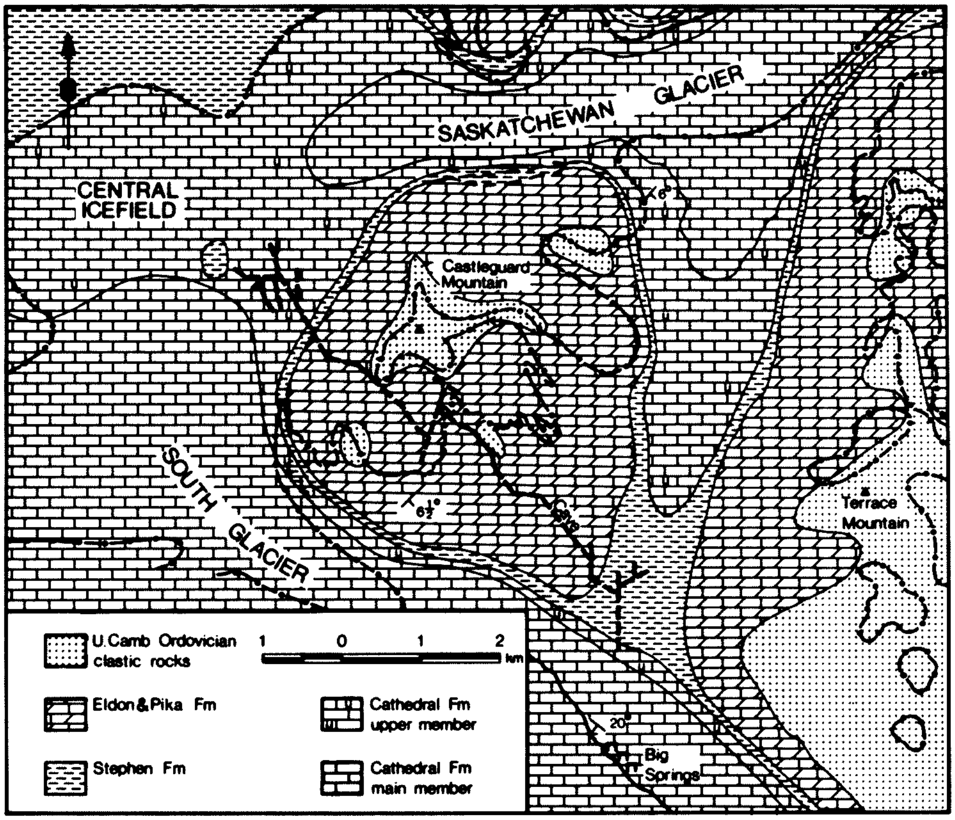

FIGURE 5. Geological map of the Castleguard area.

GLACIAL AND PERIGLACIAL FEATURES

Relevant features are shown in Figure 7. The modern glaciers are all believed to be of the temperate type, i.e., with basal ice temperatures at the pressure melting point. Ford et al. (1976) cite evidence from Castleguard Cave to suggest that the central icefield has persisted throughout at least the past 150,000 yr, always in a temperate condition at the base. Thicknesses of the relevant modern glaciers are poorly known. Waddington and Jones (1977) have published results of two north-south radio echo traverses on the northeastern part of the central icefield, between the heads of the Athabasca and Saskatchewan glaciers, with a dogleg west towards the Columbia. Ice depths ranged between 100 and 365 ± 5 to 20 m. The depth at a glacier plug in Castleguard Cave, ca. 900 m south of the limit of Waddington and Jones's traverses, is known to be 297 ± 10 m (Ford et al., 1976). Ice thicknesses of the Athabasca and Saskatchewan glaciers range between 200 and 300 m also until the glaciers thin towards the snout (Meier, 1960; Paterson and Savage, 1963). An important consequence, as indicated in Figure 5, is that most of the central icefield and upper Saskatchewan Glacier rest on the Cathedral Formation. The cirque glaciers surrounding Castleguard Mountain and in the Terrace range are believed to be little thicker than 100 m at their greatest.

Distribution of Upper Cambrian erratics indicates that all cirques, valleys and benches were occupied by flowing ice at the peak of the last major glaciation. Trimlines are poorly preserved but suggest maximum ice depths of 750 to 800 m in the Castleguard Valley.

A complex of morainic ridges and piles in the central and northern Meadows are the only local evidence of stages in the recession of the last ice. These deposits suggest a late, convergent readvance of ice from Castleguard Mountain, Terrace Mountain, and the Saskatchewan Glacier, that was of minor extent. Luckman and Kearney (1978) studied a section of lacustrine and other sediments filling a sinkhole on the proximal side of these deposits. They obtained a ^{14}C age of 9600 ± 300 BP from the earliest soil, which was confirmed by finding Mazama ash (6600 BP) higher up the section. This shows that the last major glaciation was the late Wisconsinan, and that the Meadows were ice-free and vegetated before 9600 BP. Any further late Wisconsinan readvances have been obliterated by Neoglacial ice advances.

Evidences of a Neoglacial advance are abundant and prominent (Figure 7). The Castleguard and Terrace Mountain glaciers built sharp terminal moraines up to 50 m in height. The first vegetation is just appearing upon them. The earliest photographs (A.D. 1918, Figure 3) show the ice standing at these moraines, but considerably thinned. The ice fronts have now receded an average of 500 m, exposing scoured bedrock platforms. The Saskatchewan Glacier has receded 2 km and thinned 100 m in its surviving distal parts. South Glacier plowed into dense forest, from which it has also receded 2 km. Our sporadic observations during the period 1967 to 1981 indicate that the Castleguard glaciers are now receding only slowly, with aggregate retreats ≤20 m. Saskatchewan and South glaciers have receded no more than 100 m during the same period.

The modern treeline is between 2000 and 2150 m. There is a wealth of periglacial landforms above it. The most prominent are felsenmeer which cover all Pika and Eldon bench surfaces outside of the Neoglacial moraines; they are of Holocene age. Stone polygons appear in the felsenmeer above 2350 m a.s.l., where the calculated mean annual temperature is -5°C. Clay-rich moraine of the late Wisconsinan is mobilized into solifluction lobes. In many cases it can be seen that these have advanced to partly bury karst sinkholes or pavements that are of probable Holocene age, suggesting that solifluction was greatly stimulated by the climatic deterioration of the Neoglacial (Ford, 1979). There is very little solifluction as yet upon the Neoglacial moraines themselves.

KARST FEATURES

Karst landforms are developed upon all of the carbonate formations. Karren (small-scale solutional pits, grooves, and runnels) are found on most outcrops at all altitudes. Type and form varies primarily with the lithologic differences between beds; e.g., a microcirque form termed "trittkarren" (Bögli, 1961) is limited to the one porcellanous bed outcropping in the upper Cathedral member. It is particularly interesting to observe that shallow, incipient runnel karren are already appearing on Neoglacial surfaces uncovered by ice retreat within the past 30 to 60 yr. With one exception, Neoglacial ice scour removed all earlier Holocene karren.

A different class of small-scale karst features are the deposits of calcite precipitated subglacially (Ford et al., 1970). They are found upon freshly exposed, polished and drumlinized Neoglacial surfaces on the dense, resistant Cathedral, Pika, and Eldon rocks (Figure 8). In 1970, a temporary ice cave in the snout of the southwest Castleguard Glacier permitted them to be traced 80 m into the ice.

The Castleguard deposits appear to be more extensive, larger, and more varied in morphology than those of other reported sites. They may cover ≤80% of bedrock surfaces close to the current ice fronts. Forms are highly streamlined to accord to basal ice flow directions. Deposits are ≤5 cm in depth. The composition ranges from pure, translucent, secondary calcite to opaque, silty textured material. The latter is attributable to high contents of glacier flour.

From laboratory simulations and field studies at sites in the U.S. Rocky Mountains, Hallet (1976) concluded that pressure melting at the ice base permitted local solution of the carbonate bedrock. The solute load is then precipitated in lee positions upon refreezing. The character of the Castleguard deposits supports this opinion. C. C. Smart (1983, this symposium) further develops ice-base hydrology from the karst viewpoint in his paper.

The Castleguard deposits are finest and most extensive where little or no large clastic debris can be supplied to the ice (i.e., distant from the horn of Castleguard Mountain); this implies that, once the glaciers had bulldozed off the Holocene felsenmeer described above, their erosive capability was limited to solution, a little quarrying, and flour production with the quarried debris.

Varieties of sinkholes are the principal surface karst features. On the Stephen, Pika, and Eldon rocks, they are narrow, vertical shafts elongated along guiding joints. Penetrable depth exceeds 25 m in a few cases. On the

FIGURE 6. A sedimentary (sandstone) dike standing 0.5 m proud of carbonate rocks of the upper Pika Formation. The surface is the Neoglacial base of the southwest Castleguard Glacier, exposed by ice recession since A.D. 1918. Castleguard Mountain and the southwest Castleguard Glacier are seen in the background. The glacier drains through its bed via sinkholes in the Pika rocks.

more purely calcitic Cathedral rocks, circular or elliptical shafts, 2 to 45 m in depth, predominate, but there are also funnel-shaped dolines in bedrock, the common form in extraglacial regions. Suffosion dolines, where till up to 5 m deep is funnelled into an underlying bedrock shaft, occur.

On Pika and Eldon Neoglacial surfaces it is clear that the solutional shafts antedate the Neoglacial recession. Only one shaft remains open and active on the high, cold felsenmeer surfaces in these rocks. This is kept open in a permafrost situation (mean annual temperature is -6°C) by a stream from a nearby semipermanent snowbank (Ford, 1971: 245).

Sinkholes are best developed in the upper and main members of the Cathedral Formation in the northern Meadows (Figure 9). Some are large and swallow melt streams from cirque glaciers in the Terrace Mountains. Others are small and have local snowmelt and rain catch-

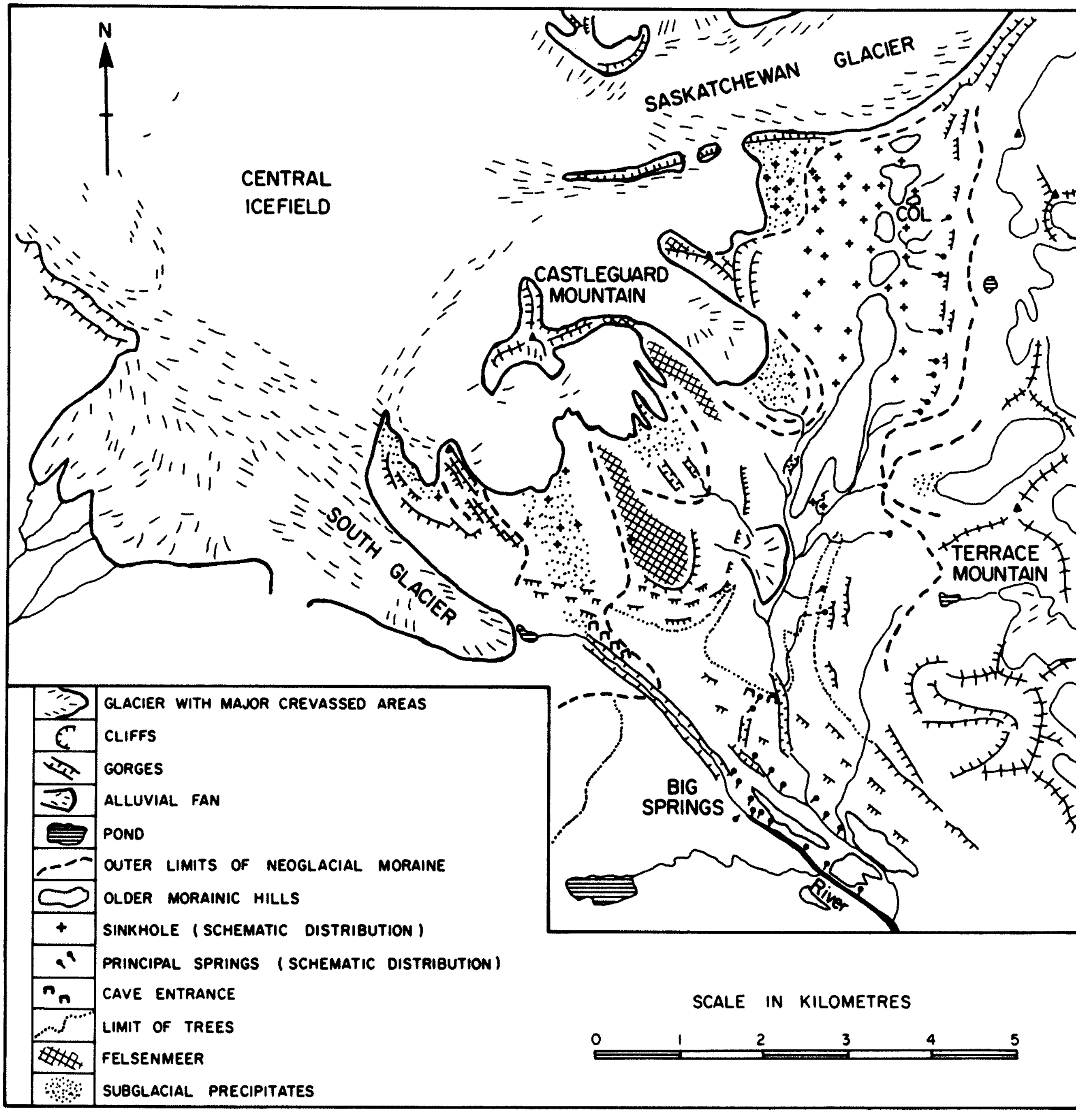

FIGURE 7. Glacial, periglacial, and karstic features of the Castleguard area.

ments of no more than 1 ha, but are integral in the modern drainage and of probable Holocene age. A few shafts appear on the crests of roches moutonnées and have no modern catchments. They were created subglacially during the late Wisconsinan Glaciation, or are earlier. Immediately outside of the Neoglacial moraine of the northeast Castleguard Glacier (2 to 30 m distant) is a line of large, deep shafts which may be attributed to supraglacial streams of the Neoglacial maximum.

There are few accessible caves. Most sinkhole shafts become impassably narrow or are infilled by dejecta at the base. Castleguard Cave is explored from its outlet in the north wall of Castleguard Valley, just below the Meadows. It is the longest natural cavern known in Canada, the raison d'être for this symposium, and analyzed in detail in later papers. Another effluent cave is known in Meadows Creek canyon, 600 m southeast of Castleguard Cave. It is impassably small and appears young. Ten small solutional caves occur in the north Neoglacial benches of the South Glacier (Figure 7). The largest example may be followed for several hundred meters before becoming impassable. All were evidently filled with flowing water when Neoglacial ice covered them, and this flow has enlarged them locally, creating some new passages. However, it is believed that many were originally opened to drain interior regions of the karst massif.

There are more than one hundred karst springs. Their distribution and regimes are complex. One family emerges from Eldon rocks at the Stephen contact along the east side of the Meadows, indicating that the Stephen Formation is an effective aquitard with respect to drainage on the west slope of the Terrace Mountain range, i.e., where groundwater drainage trends counter to stratal dip. The more interesting and provocative springs emerge in the north wall or floor of Castleguard Valley, along a distance of 5 km and over a height range of 300 m. They include perennial, seasonal, and episodic springs. Their aggregate discharge is large, making them (we believe) the principal headwater source of the North Saskatchewan River, although the Saskatchewan Glacier is its official source. The difference in elevation between the highest observed modern sinkpoints and the lowest springs exceeds 1000 m. This system, particularly its springs, is considered in detail by C. C. Smart (1983, this symposium).

Ford (1971) reported upon hydrochemical characteristics of the karst waters. Later analyses have confirmed those findings. The most important feature is that many subglacial waters passing through the karst are strongly depleted in their solvent potential with respect to calcite, becoming saturated with the mineral when they have dissolved no more than 25 to 30 mg/L. Calcite solubility in a standard atmosphere at 0°C is 75 mg/L. Aspects of this problem are considered by Atkinson in this symposium.

From the sum of karst evidences available in 1970, Ford (1971) proposed the following model for the genesis of the karstic groundwater system: (1) Castleguard I—the drained and relict Castleguard Cave. This was believed to have been abandoned as a consequence of glacial erosion entrenching below its inlets during episodes of the Wisconsinan Glaciation. (2) Castleguard II—a modern, inaccessible system approximately underlying Castleguard Cave and draining portions of the central icefield to the principal springs in Castleguard Valley. (3) Castleguard III—a tributary of Castleguard II, draining the northern Meadows. As a tributary it would be somewhat younger, e.g., of late glacial-postglacial age.

Readers will find it instructive to consider the extent to which subsequent work has changed our views of the complexity and antiquity of the Castleguard Karst.

FIGURE 8. Subglacial calcite precipitates (white material) exposed on a Neoglacial surface. Stoss ends of bedrock microdrumlins show up as gray, arcuate features free of the precipitate. Ice flow was towards the camera.

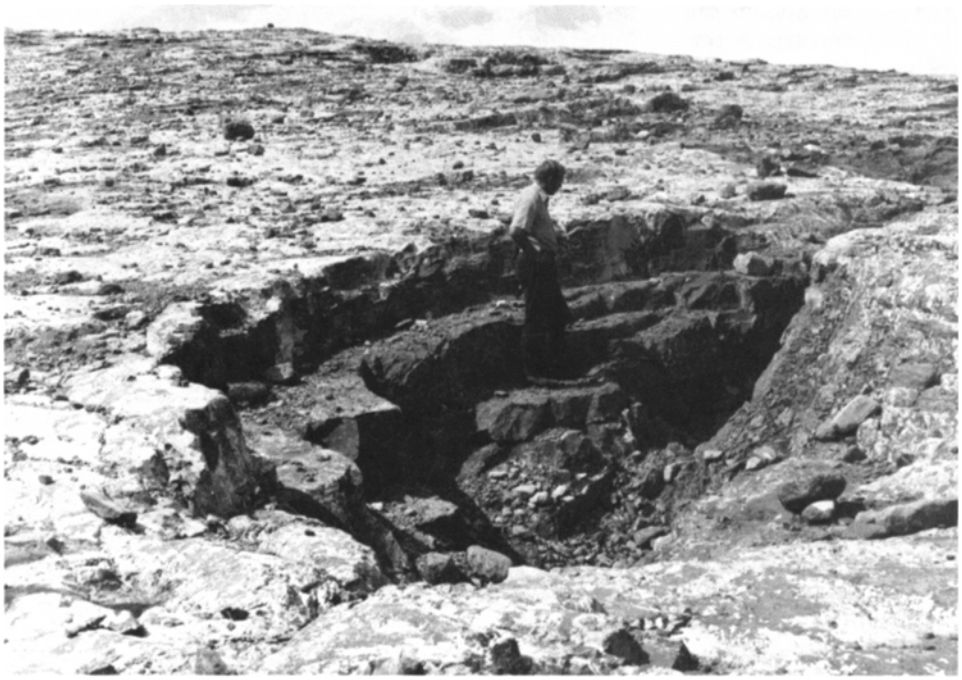

Figure 9. A small solution sinkhole in upper Cathedral strata exposed on a Neoglacial surface below the northeast Castleguard Glacier. White material is subglacial precipitate. The sinkhole was overridden by ice flowing from left to right. This quarried the upstream wall of the sinkhole and abraded the downstream wall, to produce a negative landform that is the precise converse of the roche moutonnée.

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