Article

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STRUCTURALLY-CONTROLLED FLUVIOGLACIAL EROSION FEATURES NEAR SCHEFFERVILLE, QUÉBEC *

by

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Schefferville, located almost at the centre of the Quebec-Labrador Peninsula (Figure 1), lies within the area which witnessed the penultimate stages of the final disintegration of that eastern remnant of the Laurentide ice-sheet, which Laverdière would prefer to call the Scheffer ice-cap (Laverdière, 1967, 1968, 1969a, 1969b), and which did not finally disappear until shortly after 5,000 B.P. (Bryson, Wendland, Ives and Andrews, 1969). Recently, there has appeared in the literature a rather involved and spirited discussion as to the location of the final disappearance of this ice-body (Laverdière, 1967, 1968, 1969a, 1969b ; Barnett and Peterson, 1968 ; Ives, 1968) ; despite the intricacies of this discussion, it remains well established that with respect to the Schefferville area, a disintegration divide ran approximately ENE to WSW through the site of the present-day Kivivic Lake, some 30 miles NW of Schefferville (Ives, 1960). From the evidence of till fabric orientations and those of eskers, drumlins, and other ice-moulded forms, it would appear that this area also acted as an ice-dispersal centre at a somewhat earlier period (Kirby, 1961a ; 1961b). It should perhaps be mentioned that Laverdière (1969a) considers that the till fabric orientations reported by Kirby, and the meltwater channel alignments discussed by Ives, « *ne peuvent avoir que des significations locales* » (Laverdière, 1969a, p. 240), related to an isolated remnant, detached from the main body of the Scheffer

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* The field-work on which this article is based also formed the basis of a Master's degree from McGill University, and was undertaken in 1964, while the writer was a research assistant at the McGill Sub-Arctic Research Laboratory at Schefferville. The facilities and materials made available by the Laboratory, including aerial photographs, library facilities, surveying and camping equipment, and transport, were quite invaluable. In particular, I wish to thank the Director, Dr. W.P. Adams, who held that position from 1963 to 1966, for his unfailing enthusiasm and encouragement, Dr. James S. Gardner for his help in supplying transport, and my brother Mr. Douglas Barr for his invaluable work as field-assistant.

Foremost among the other organizations and individuals who greatly assisted me in Schefferville, was the Iron Ore Company of Canada, in allowing me access to its aerial photograph library, in supplying detailed topographic maps and not least, in constructing a net-work of exploration roads, which made the whole field-area easily accessible. I also wish to thank Dominion Helicopters, particularly Captain Black, for providing an opportunity for an aerial reconnaissance of the field area, and Mr. W.R. Cowan for the photograph reproduced as Photo 3.

I also wish to acknowledge the help and encouragement of Professor J. Brian Bird, and Professor John T. Parry of the Department of Geography, McGill University. Generous financial support was received from the Centre d'Etudes nordiques at Laval University, Quebec, and from the Arctic Institute of North America. The study and library facilities provided by the latter organization were also greatly appreciated.

ice-cap, which was meantime disintegrating further west. Be that as it may, the coincidence of a late-glacial ice dispersal centre, with a later disintegration centre just to the northwest of Schefferville, resulted in the flow of large quantities of meltwater in a south-southeasterly direction across the Schefferville area. Meltwater flow, originally englacial, became increasingly subglacial with the thinning of the ice-mass. Impingement of the meltwater streams on the bedrock resulted in an abundance of meltwater channels throughout the area (Derbyshire, 1962).

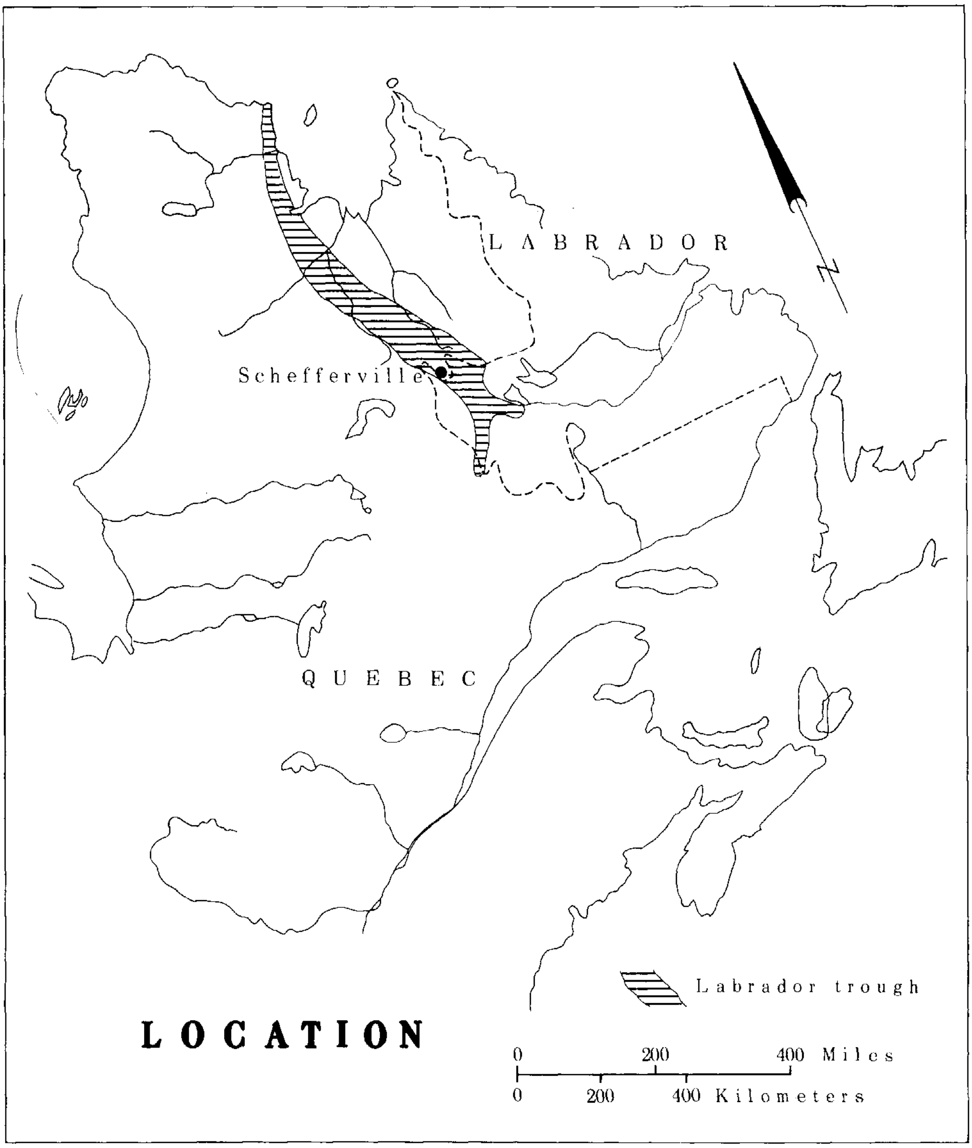


Figure 1 *Location of the field study area, and general outline of the « Labrador Trough ».*

The alignment of these channels is generally in a NNW-SSE direction. This is not fortuitous, but is directly related to the location of the Schefferville area with respect to the former late-glacial ice dispersal centre some 30 miles NW of Schefferville. The concept that the general direction of englacial and subglacial meltwater flow would be controlled not by subglacial topography, but by the maximum gradient of the ice surface, has been elaborated in some detail by Gjessing (1960, 1966). In other words, the direction of the maximum surface gradient, which on the basis of the geomorphological evidence presented by Kirby (1961a, 1961b) must have been from NNW to SSE, would produce an equivalent englacial and subglacial hydraulic gradient controlling the general direction of meltwater flow.

While the general alignment of the meltwater channels is thus controlled by the gradient of the former ice-cover, some of the more striking details of the channels are controlled by rock structure. The importance of bedrock control was stressed by Ives and Kirby (1964, p. 917) who pointed out that :

> « The bedrock structures closely control the topography and can be expected to exert strong lithological influence on the morphology of water-cut glacial features ».

However, there has as yet been no published work concentrating solely on the degree to which the meltwater channels in this area are structurally controlled in their form and alignment. This paper is an attempt at rectifying this situation. While it must be stressed that all channels in the area display significant evidence of bedrock structural control, the main emphasis will be on two distinct types of channels : arcuate channels, and the features originally mis-named *vallons de gélivation* (Derruau, 1956 ; Twidale, 1956, 1958), but which will here simply be referred to as *vallons.* In each case, bedrock structure is the dominant control of these fluvioglacial forms.

Geology and general physiography

It should be stated at the outset, that the Schefferville area is structurally rather unusual, and that the degree of structural control in the topography is generally abnormally high. Schefferville lies within the belt of Proterozoic rocks commonly referred to as the « Labrador Trough », which stretches from Cape Hope's Advance to the southwest corner of Labrador (Figure 1). The « trough » reaches a width of about 60 miles in the Schefferville area. As Harrison (1952, p. 17) pointed out, the term « trough » is not strictly accurate, since the opposite sides do not match, and since the strata dip mainly towards the northeast across its entire width. The Proterozoic rocks were deposited in a broad geosyncline, and have subsequently been folded and faulted to their present position. They rest, with a very marked unconformity, on the Archaean basement complex of gneisses known as the Ashuanipi group. There is a marked variation in the thickness of the Proterozoic rocks from place to place, but an approximate estimate of the average thickness would be in the order of 20 000 feet ; the amount removed by erosion is unknown.

Harrison (1952), from whose work most of the geological information is derived, applied the name « Knob Lake Group » to the sedimentary succession. The details of the various formations are included in Table I. In some cases, the formations extend for many miles along the strike, and are repeated in almost every thrust slice. In other instances, the formations may occur only locally, and vary widely in thickness.

Table 1 ***Stratigraphic sequence in the Schefferville area***
(Modified, after Harrison, 1952)

Era	*Group*	*Formation*	*Lithology*
PROTEROZOIC	KNOB LAKE	Menihek	Creamy grey to jet-black carbonaceous slate ; varying amounts of impure dolomite ; greywacke ; pyritiferous slate ; minor chert.
			unconformity ?
		Sokoman	Iron formations with the following members : banded silicate ; thin-banded jasper ; banded cherty ; thick-banded jasper ; cherty metallic ; cherty iron carbonate ; massive cherty ; lean chert ; slaty members.
		Ruth	Black to greenish black, ferruginous, carbonaceous slate ; some chert interbeds, locally abundant ; base is black massive chert.
		Wishart	Quartzite ; arkose ; minor slaty and calcareous beds near base ; minor cherty beds at top.
		Fleming	Massive chert ; chert-breccia ; quartzite with chert cement ; chertified slate ; conglomerate of chert pebbles in matrix of chert cemented quartzite.
			disconformity ?
		Denault	Dense dolomite, weathering to buff or grey ; arenaceous dolomite ; dolomite breccia cemented by dolomite and/or chert ; cherty dolomite ; minor slaty and quartzitic interbeds.
		Attikamagen	Varicoloured slate ; local interbeds of dolomite ; porous granular chert in lowest exposures.
		unconformity	
ARCHAEAN	ASHUANIPI		Biotitic, hornblende, garnetiferous, and granitic gneisses ; amphibolites ; granitic intrusions.

The most important formation, with respect to the present study, is the Attikamagen Formation, lying unconformably on the Archaean rocks at the base of the group. Exposures range in thickness from 100′ to 1200′. The formation consists mainly of slates and argilites, usually yellowish to greenish grey in colour, but also red, violet, green, buff and brown. These are extremely fine-grained rocks, and are extremely fissile. They appear to be particularly susceptible to frost-action, and the outcrops exposed in meltwater channels are invariably swathed in postglacial talus.

The overlying Denault Formation consists predominantly of dolomites, with a total thickness of up to 600 feet. They are generally massive and well-bedded, and when weathered are brownish in colour. When fresh, they are greeny-grey in colour, and are shot through with nodules, seams and veins of chert. As a result, these dolomites form easily identifiable erratics, although, due to the abundance of possible sources, they are of little help in determining ice-movement directions.

Towards the top of the group is the Sokoman Formation, the only other formation with direct relevance to this study, and the most important formation with respect to the Schefferville iron-mining operation, in that it contains the bulk of the iron-bearing rocks. The Sokoman Formation varies quite widely in lithology, and includes banded silicate-carbonate, banded jasper, massive chert-haematite-magnetite, banded chert-siderite-iron oxide, sideritic slate, jasper conglomerate, and magnetic greywacke and slate (Frarey, 1957).

Since deposition, the Knob Lake Group has undergone intense folding and faulting. Locally, on the southwest side of the trough, the rocks are almost undisturbed, but generally there is clear evidence of considerable pressure having been exerted from the northeast. This has resulted in numerous high-angle thrust faults, trending NW-SE, and in very severe folding. As Harrison has pointed out (1952, p. 15), the characteristic structure is the overturned anticline, with the overturned limb truncated along a thrust fault. The angle of pitch of the folds is often less than 25°, but locally, as will be demonstrated later, it may exceed 50°.

Despite the intense pressures which the sediments have undergone, only a slight degree of metamorphism has resulted. Only locally has the degree of alteration been great enough to obscure the original character of the rocks. Thus, even in the slates of the Attikamagen Formation, bedding is still quite clear, and cleavage is still along the original bedding planes.

The result of the intense folding and faulting is a very marked NW-SE trend to the structure, with various parts of the sedimentary sequence being exposed repeatedly in successive thrust-slices, along any NW-SE transect. Fluvial and glacial erosion of the contrasting rock-types in this remarkably linear structural foundation, has produced a topography which displays an equally striking pattern of parallel ridges and valleys, aligned from NW to SE (Photo 1). The relative relief is generally only slight, with the parallel ridges rarely rising more than 300′ above the intervening valleys. A reflection of the persistent northeasterly dip is to be seen in the occasional occurrence of assymetric ridges, with the gentler slope lying to the northeast down the dip.

Structural control of meltwater channels

In an area where the topography in general is so markedly influenced by bedrock structure, it is to be expected, that when the englacial meltwater streams were let down on the substrate due to ice thinning, they, too, would be greatly influenced by the structure. In view of the fairly close parallelism between the alignment of ice-directed subglacial and englacial drainage (NNW-SSE) and the alignment of the folds and thrust-faults (NW-SE), it was almost inevitable that the majority of the channels should have followed the strike, and as a result, are remarkably straight (Photo 2).

Photo 1 *Structurally-controlled ridge-and-valley topography, west of Schefferville. Distant hills lie beyond the western boundary of the « Trough », and are developed on the underlying Archaean rocks.*

Photo 2 *A straight strike-aligned channel on the east flank of Ruth Ridge.*

Photo 3 *An aerial view of « Hung-up Channel », showing the main features of this structurally controlled subglacial arcuate channel.*

The most interesting channels in the Schefferville area, however, deviate markedly from this pattern, yet on examination, were also found to be strictly controlled by structure in their form and alignment. These are a group of three arcuate channels (Photo 3), lying about eight miles south of Schefferville, and incised into the western flank of Houston Mountain, one of the ridges bordering the broad linear depression in which the town is located (Figure 6). An associated channel runs along the foot of the slope below the arcuates (Figure 2). The details of the geology are presented in Figure 3. Most of the area consists of Attikamagen slates. Very significantly as regards the fluvioglacial history, there are, within the slates, several very tight folds, both anticlinal and synclinal, pitching steeply towards the SE. To the west, at the foot of the slope, the slates give way to the basal beds of the overlying Denault Formation. Running from north to south across the hillside, is one of the two near-vertical diabase dykes which traverse the Schefferville area. It is rarely more than 2 or 3 yards wide, and dies out among the Attikamagen slates to the north. There is clear evidence of very localized thermal metamorphism of the slates in immediate contact with the dyke, and there is evidence of some vertical displacement, with the upthrow to the east.

Figure 2 illustrates the relative positions and altitudes of the three channels. « Hawk's Nest Channel » so named for the nest of a Rough-legged Hawk on its cliffs, is the largest and most impressive of the three arcuates. It averages 270 feet in width from lip to lip, and reaches a maximum width of 390 feet at the apex of the bend, where the channel swings from a south-easterly to a westerly direction. The depth is 90 feet at the point where a cross-section was measured (Figure 4). At the apex of the bend, however, where the free-face reaches its maximum height, the total depth is estimated at 120 feet, of which at least 30 feet is a near-vertical rock face.

A careful levelling traverse revealed that the channel rises fairly steadily from its northern intake, where it hangs at a height of 86 feet above « Tamarack Channel ». The total rise in the profile of this section of the channel amounts to 51 feet over a distance of 1178 feet, giving an average gradient of 1:23 (Figure 5). The floor of this section of the channel is partially obscured by thick birch scrub, and by postglacial talus, but bedrock outcrops occur in the floor of the channel at the summit, indicating that this is an up-and-

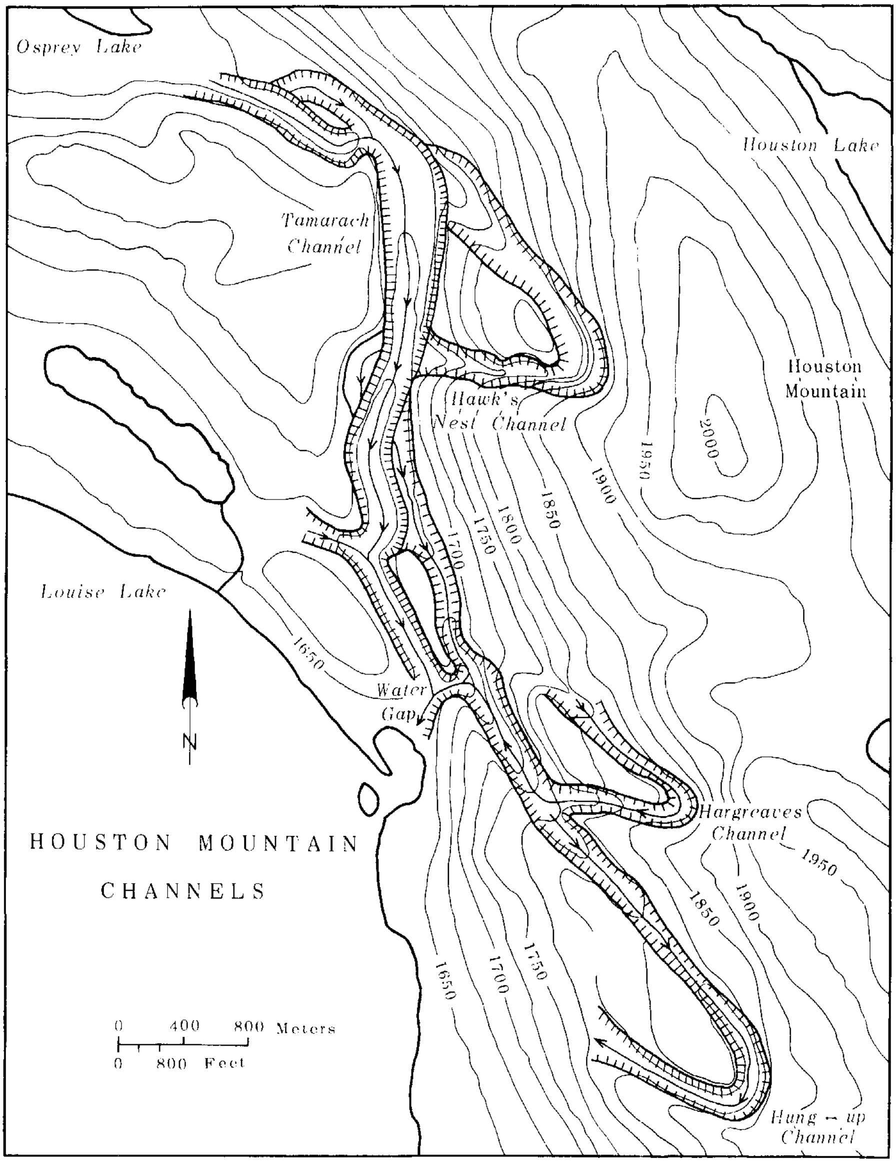


Figure 2 *Houston Mountain : relationships between the channels and the topography.*

down profile. From the summit, the channel drops steadily back down to « Tamarack Channel » again. The total drop is 115 feet over a horizontal distance of 1331 feet, giving an over-all gradient of 1:12. For a short distance, this reaches 1:7.

Around much of the outer perimeter of the curve of the channel the Attikamagen slates support a free face rising to a height of 30-35 feet. Beneath this extensive talus slopes, reaching a maximum height of 90 feet

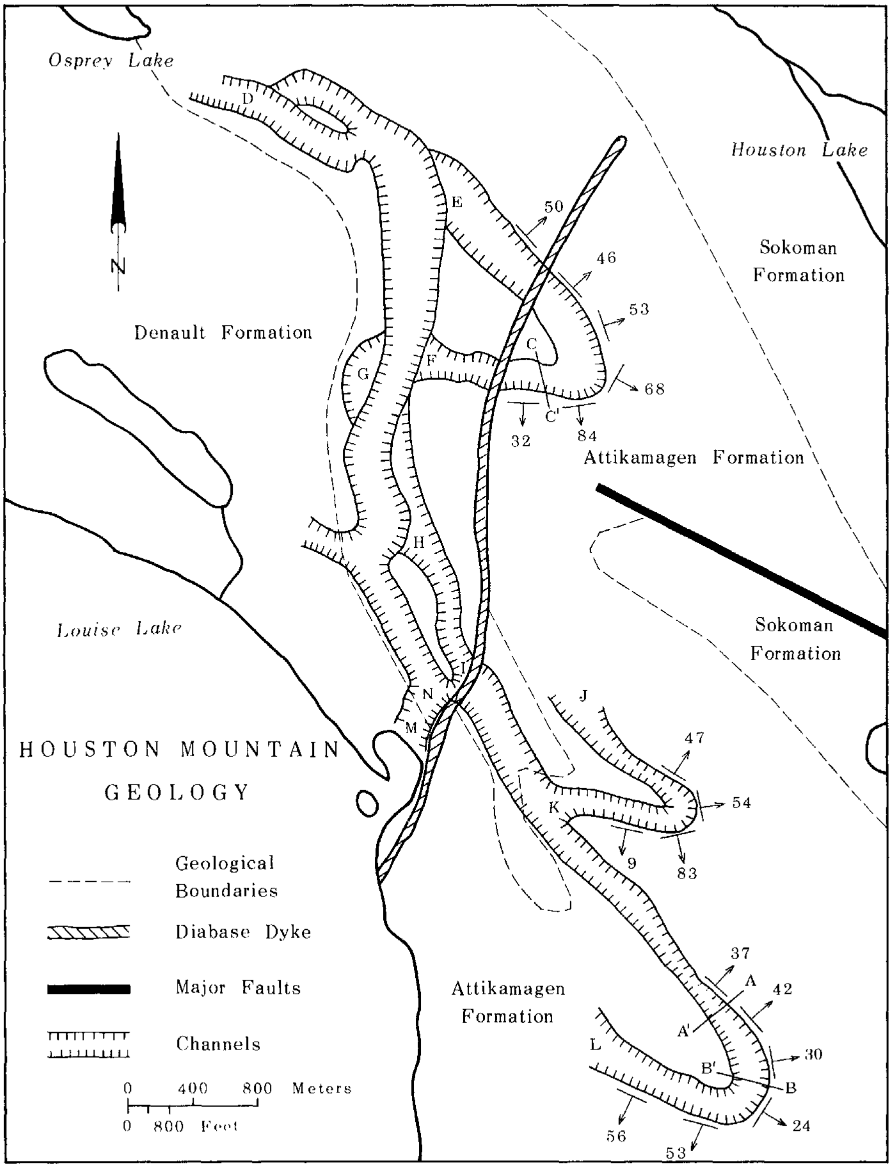


Figure 3 *Selected geological features of the Houston Mountain area. Cross-sections A-A_1, B-B_1, and C-C_1 are illustrated in Figure 4. Letters locate long-profiles presented in Figure 5.*

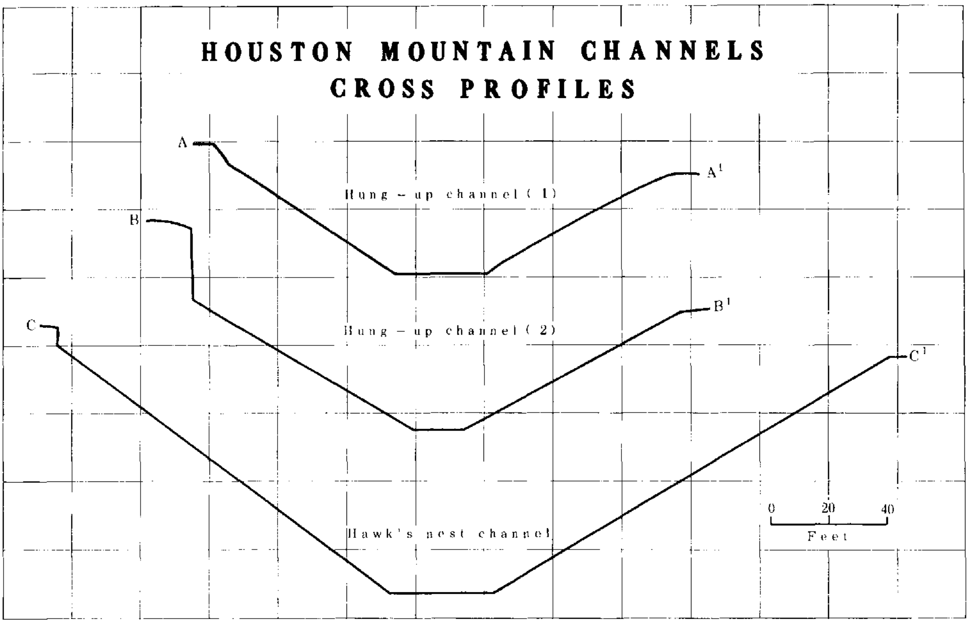


Figure 4 *Cross-sections of the arcuate channels ; positions are located on Figure 3.*

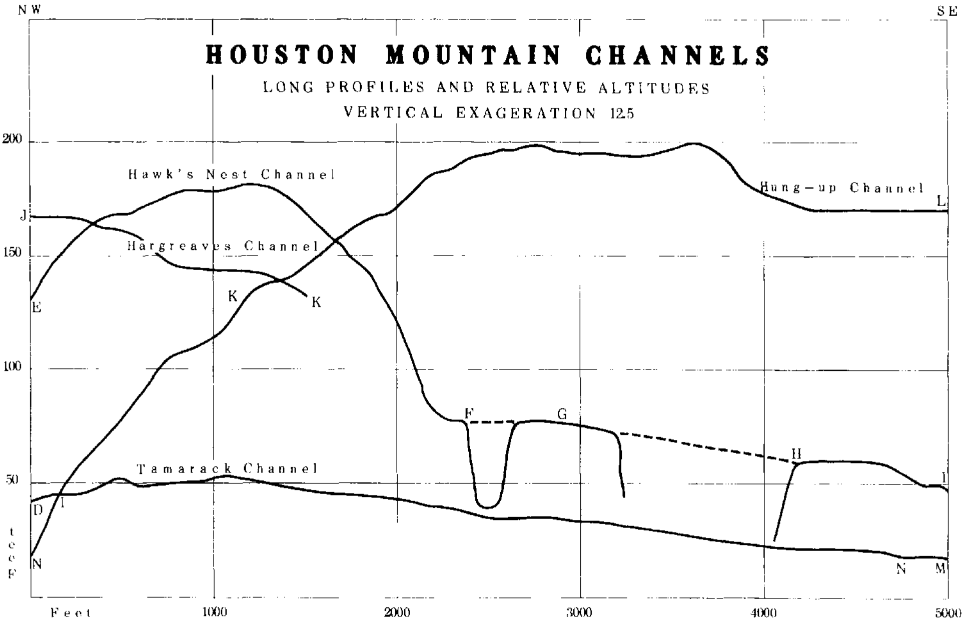


Figure 5 *Long profiles and relative altitudes of the Houston Mountain arcuate Channels. Letters locate the profiles with reference to Figure 3.*

stretch down to the channel floor at a fairly constant angle of 27-30°. In a few places, the talus has become fixed by vegetation, but generally it is highly mobile, due largely to the nature of the slate fragments of which it is composed. In contrast, the slopes on the inner side of the curve are quite heavily vegetated, the main species being Black Spruce (*Picea mariana*), White Spruce (*Picea glauca*), Dwarf birch (*Betula glandulosa*), and alder (*Alnus crispa*). This vegetation has established itself on a talus slope similar to that of the other side of the channel. Talus accumulation has in places reduced an original flat-bottomed cross profile to a V-shaped one. Elsewhere, however, (Figure 4) the flat-bottomed cross profile is still apparent.

The most revealing geological clue as to the mode of formation of this channel is the relationship between its alignment and the dip of the rocks. Measurements of the dips around the outer perimeter revealed that at all points, the rocks dip at high angles away from the channel, i.e. the channel is aligned around the nose of a steeply pitching anticline (Figure 3).

These various characteristics are repeated on a smaller scale in the other two arcuate channels. Most significantly, in all three channels, there is the same close relationship between channel alignment and the dip of the strata, indicating that all three follow the strike around the noses of pitching anticlines. Moreover, all three channels display up-and-down bedrock long profiles. In the case of « Hung-up Channel », a very interesting feature is the way in which the channel outlet ends abruptly on the hillside at about 160 feet above Louise Lake. There is no indication of either fluvio-glacial erosion or deposition on the hillside below this outlet.

Along the foot of the slope, and cutting across (hence post-dating) the lower part of « Hawk's Nest Channel », is a longitudinal channel, here referred to as « Tamarack Channel ». It begins at the south end of Osprey Lake and rises gently southwards for some distance, becoming increasingly incised as it crosses the divide. (The latter separates the Churchill from the Kaniapiskau drainage, and also marks the Quebec/Labrador boundary.) A small pool some 14 feet in depth is located at the summit of the channel ; as the total rise in the channel long profile to this point is only 20 feet, it is quite conceivable that the bedrock profile may drop steadily southwards from Osprey Lake, with the apparent up-and-down profile being due to talus and peat accumulation. From the summit southwards, marshy pools cover much of the bed of the channel, and a small misfit stream meanders along between banks of peat and alluvium.

The alignment of the channel is quite tortuous, with several very marked right-angled bends, possibly structurally controlled. The final section is remarkably straight, and is definitely structurally controlled. On the west the channel is bounded by a wall-like face of well-bedded dolomites of the Denault formation, dipping steeply towards the east (Photo 4), and on the east by a much gentler slope developed on Attikamagen slates. This is a surface expression of a structural feature typical of the Schefferville area — the overturned fold. The wall-like face exposes the original undersides of the basal beds of the Denault formation in the lower limb of an overturned fold, whose upper part has long since been removed by erosion. When the meltwater stream impinged on this junction between the dolomites and the slates, it was guided along the strike, and eroded its channel mainly in the slates.

Two further points should be mentioned in order to complete this account of fluvioglacial activity in the Houston Mountain area. Firstly there is no significant fluvioglacial deposition in the area. Secondly, bedrock is exposed over a large area of the hillside ; any drift which might have been deposited has been stripped off, and the bedrock heavily scoured, presumably by fluvioglacial action (Photo 5).

Interpretation of the field evidence

There are three main points which must be reconciled in any attempt at interpreting this complex of meltwater channels. These are : 1) the up-and-down long profiles, 2) the arcuate configuration of the channels, and 3) the sequence of development, since clearly all the channels were not formed simultaneously.

It is almost impossible to conceive of channels with up-and-down long profiles having been formed subaerially either as marginal or proglacial channels or as overflows from ice-dammed lakes, although some very imaginative theories involving reversal of flow, and some very intricate shifts in ice marginal positions to produce the necessary ice-dammed lakes, have been proposed to explain channels of this type in Britain (Peel, 1951 ; Twidale, 1956 ; Eckford, 1952 ; Common, 1957 ; Drehwald, 1955, p. 18) where Kendall's classic interpretation of the Cleveland Hills meltwater channels (Kendall, 1902, 1903) as lake overflows long influenced the fluvioglacial literature. A much more plausible explanation of meltwater channels with an up-and-down profile is that they were eroded by a subglacial meltwater stream which was capable of limited uphill flow and erosion where there was the necessary hydrostatic pressure. This hypothesis was first enunciated by Tanner (1915), to explain a channel which displayed a rise of 30m in its long profile, in Finnish Lappland. Since then, with the general acceptance (somewhat belatedly in Britain) of the related concepts of progressive downwasting of the ice masses, and of extensive englacial and subglacial meltwater flow during the penultimate stages of deglaciation (e.g. Mannerfelt, 1938, 1940, 1945, 1949, 1960 ; Hoppe, 1950, 1957, 1959 ; Strom, 1945, 1956 ; Sund, 1943 ; Rudberg, 1948 ; Nordnes and Sund, 1953), the idea of limited uphill flow and erosion by subglacial meltwater streams has become almost universally accepted (e.g. Gjessing, 1960, 1966 ; Sollid, 1964 ; Trömborg, 1964 ; Schou, 1949 ; Weinberger, 1953 ; Sissons, 1958a, 1958b, 1960, 1961a, 1961b). There seems little doubt that the 50 foot rise in the northern limb of « Hawk's Nest Channel », and the lesser rise in « Hung-up Channel » could only have been produced in such a manner, as the result of local uphill flow in a subglacial meltwater stream.

The arcuate configuration of the three channels can not easily be explained in terms of earlier suggestions as to the development of arcuates. Arcuates or in-and-out channels form one of the four major groups in Kendall's classification of meltwater channels, and are explained in terms of erosion by a marginal meltwater stream flowing around a projecting ice-lobe (Kendall 1902, p. 483). This interpretation has been repeated on numerous occasions since then, e.g. Smith, 1932, p. 70. Derbyshire (1958, p. 192) also stated that arcuates owe their origin to the diversion of marginal meltwaters round a projecting ice lobe, but later (1960, p. 8) suggested that they might be formed by the deviation of a marginal stream from the ice margin as a result of topographic irregularities. This would involve something similar to Mannerfelt's extra-lateral channels or wash-out serpentines (Mannerfelt, 1945, Fig. 38). Sissons (1961a, p. 28) rejected the traditional view of marginal drainage guided by a projecting ice lobe, and suggested that arcuates might be produced by the fortuitous super-

Photo 4 *The wall-like face developed in the basal beds of the Denault Formation on the southwest side of the final straight stretch of « Tamarack Channel ».*

Photo 5 *Rugged bedrock surface produced by severe meltwater scouring of highly contorted Attikamagen slates.*

imposition of the meanders of an englacial stream which had been let down on to bedrock.

When one considers the field evidence in the Houston Mountain area, it becomes apparent that none of these hypotheses is applicable in this case. The up-and-down bedrock profiles immediately rule out the possibility of subaerial drainage, either marginal or extra-marginal, quite apart from the improbability of the ice-marginal positions which this would require. From the way in which the meltwater stream was guided by the structure, it is equally clear that these arcuate channels are not simply the result of fortuitous superimposition of englacial meanders. These, then, are structurally controlled subglacial arcuate channels.

Stenborg (1969) has recently published the results of his studies of meltwater drainage in present-day glaciers ; these studies were mainly confined to valley-glaciers, however, and one should proceed with caution in applying his findings to the conditions prevailing in the latter stages of the Laurentide ice-sheet. As Stenborg himself points out, « A drainage model established on a valley glacier clearly cannot be applied to the conditions prevailing in large ice-sheets » (Stenborg, 1969, p. 40).

Nevertheless his work provides a general background. In general Stenborg favours Glen's (1954) theory of meltwater penetration based on the pressure differences between ice and water at the bottom of a waterfilled hole in the ice. As Stenborg stresses, however, this mechanism requires an initial depth of about 150m, which is generally far in excess of the depth of the crevasse zone. How, then, does the meltwater initially penetrate to such a depth ? This query is as yet unanswered, but clearly the answer will throw light on the deglaciation and the resultant fluvioglacial phenomena in an area such as that around Schefferville.

The sequence of events tentatively proposed is as follows. At a late stage of the deglaciation of the peninsula as a whole, but at an early stage of the deglaciation of the Schefferville area, and certainly prior to the emergence of the ridge-tops from the ice, a major englacial stream, guided in its general direction of flow by the ice-surface gradient, flowed in a south-south-easterly direction along the Schefferville depression. The depth within the ice at which such an englacial stream might be expected to flow is a matter of some conjecture. Gjessing (1960) has mapped meltwater channels running continuously downslope through a vertical range of over 500 feet. Sissons (1963) however, estimated that the probable maximum depth for the zone of englacial meltwater activity is between 300 and 400 feet. While it is dangerous to draw analogies between conditions prevailing during the deglaciation of Britain, and the deglaciation of Quebec-Labrador, it seems reasonable to assume that the summit of Houston Mountain was covered by several hundred feet of ice, when the englacial meltwater stream first impinged on bedrock.

As Clapperton (1968, p. 209) has suggested, one must think in terms of an upper zone of englacial meltwater activity, limited in depth by ice which was impermeable to meltwater penetration. As the ice surface progressively down-wasted, the lower limit of meltwater penetration was correspondingly lowered, eventually resulting in superimposition on to the bedrock. Geomorphic evidence of this lower limit of meltwater penetration is to be found in the Houston Mountain area in the form of the outlet of « Hung-Up Channel », which ends so abruptly on the hillside above Louise Lake. The lack of either fluvioglacial erosion or deposition lower down the slope indicates that the meltwater stream reverted to an englacial course at this point. That this lower limit of meltwater penetration was progressively lowered as down-wasting proceeded, is indicated in the way in which the arcuates have their outlets at progressively lower levels, until Tamarack Channel follows the valley bottom almost throughout its course.

It seems probable that the initial impingement of the meltwater stream on to the projecting flank of Houston Mountain would account for much of the widespread meltwater scouring of the bedrock. Alternatively, this may date from the period when the ridge-top finally emerged from the ice, no doubt accompanied by extensive seasonal meltwater activity. Originally, the subglacial flow across the hillside would have been in a south-south-easterly direction, i.e. the direction of ice-controlled englacial and subglacial meltwater drainage. The meltwater stream must soon have become incised, however, and incision would have been accompanied by diversion, as the pitching anticlines in the slates induced the meltwater stream to flow in a sinuous pattern, producing the arcuate channels.

From the way in which « Hargreaves Channel » has been superimposed on « Hung-up Channel » and « Tamarack Channel » on all three arcuates, but especially on « Hawk's Nest Channel », (Photo 6) this is clearly a temporal sequence. « Hung-up Channel » was formed first, with the flow being southwards up the east limb, and northwestwards down the western limb. A slight change in internal ice conditions would be sufficient to move the point of impingement slightly to the east, so that « Hargreaves Channel » was next eroded, with the flow being southwards along the east limb and north down the west limb, which was superimposed on the intake of « Hung-up Channel ».

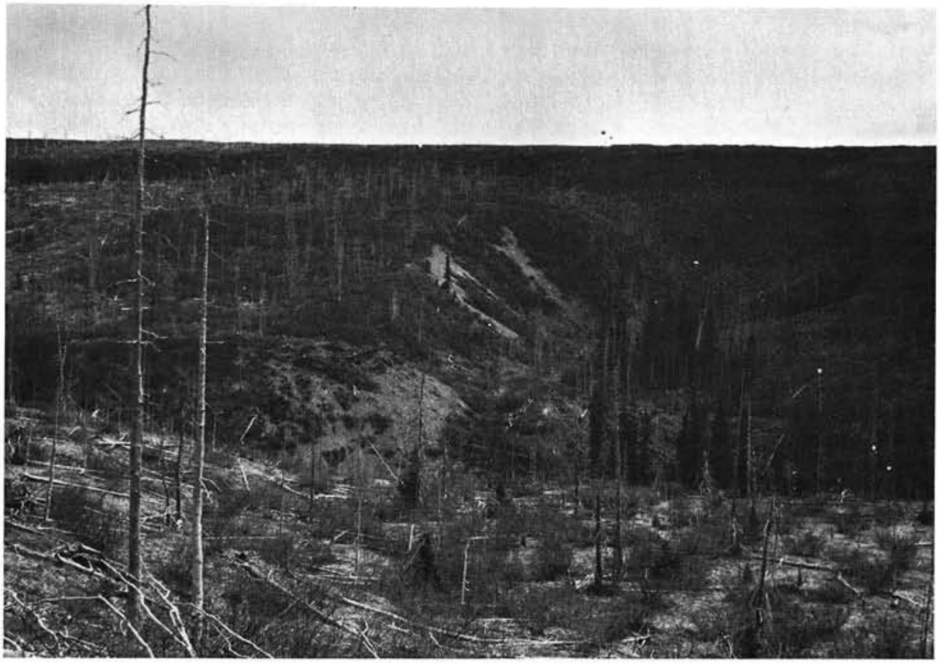


Photo 6 *Superimposition of « Tamarack Channel » across « Hawk's Nest Channel » ; the former runs from left to right across the photograph.*

By now the meltwater was able to penetrate almost to the valley-bottom in the area of the Water Gap (Figure 2). A further change in ice conditions moved the point of impingement north and east again to produce « Hawk's Nest Channel ». After flowing through the arcuate channel, the stream swung southwards as indicated by the arcuate bench on the west side of « Tamarack Channel » and continued as far south as the « Water Gap » which was cut at this time. Here the meltwater stream was guided westwards across the strike by the diabase dyke (Figure 3). Finally, in the penultimate stage of subglacial meltwater flow, « Tamarack Channel » was cut, slicing across the sinuosities of the earlier channel, but still being quite markedly controlled by the structure.

Thus, the Houston Mountain channels can best be described as structurally controlled subglacial arcuate channels. While the original impingement of the englacial stream on to the bedrock in an area of tightly folded slates was purely fortuitous, the guidance exerted thereafter by the folds on the alignment of the meltwater channels produced was far from fortuitous. Control of the form of meltwater channels by bedrock structure to this degree has not been reported from elsewhere, but is relatively common in the Schefferville area.

Vallons

Another geomorphological feature in the Schefferville area which displays clear evidence of structural control of subglacial meltwater erosion, is the form generally referred to as *vallons de gélivation*. They have been previously described and discussed by Derruau (1956), Twidale (1956 ; 1958) and Andrews (1961 ; 1963), but further evidence as to their mode of formation justifies further discussion.

The essential characteristics of this form are displayed by one of a group of *vallons* near Osprey Lake (Photo 7) ; a rock-walled dry valley is cut into a hillside at right-angles to the trend of the contours. It is 348 feet in length, and rises gradually headwards at an average angle of 8°, although broken by bedrock steps. The valley is 84 feet wide, with almost perpendicular rock walls, rising to a height of 25 feet at the inner end. At the back is a steep head-wall cut in bedrock. The bed of the *vallon* is V-shaped in cross-profile, due to in-filling by talus during postglacial time. The rocks into which this feature is cut are Attikamagen slates, with a dip of 50-58° towards the northeast ; the *vallon* faces west-southwest. At its lower end, it hangs markedly on the hillside above Osprey Lake, at the same altitude as do the other four in the group. There are signs of only slight deposition at the lower end.

The *vallons* discussed by the three previous writers lie on the west side of Dolly Ridge, some two miles northeast of Schefferville. Here there are six *vallons* almost identical to the one described above, although their dimensions are generally somewhat smaller. A further group of six features, some of which completely breach the ridge, were considered by Andrews (1961 ; 1963) to be related forms.

Derruau (1956) considered these *vallées de gélifraction* on Dolly Ridge to be periglacial in origin. He ascribed their formation to freeze-thaw action on the slates, with the steep head-walls being structurally controlled by faults crossing the *vallons* at right angles. The material thus weathered from the rock-faces was removed by nivation and solifluction. The rock-steps, often with a closed bedrock depression behind, were explained by Derruau

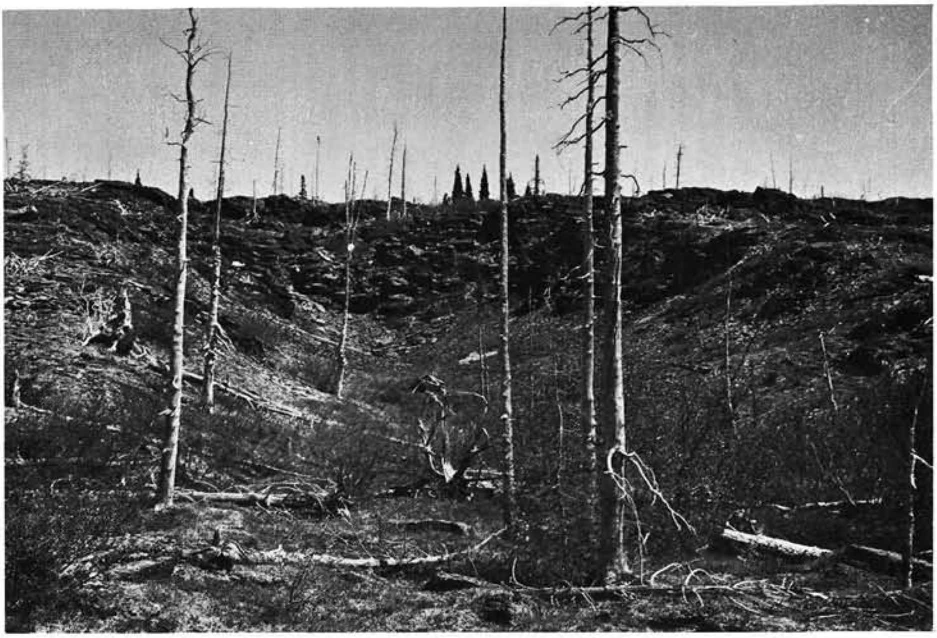


Photo 7 *One of the « vallons » near Osprey Lake, illustrating the steep rock-cut headwall, and the V-shaped cross-profile, resulting from postglacial talus in-filling.*

as being due to the movement of the frost-shattered material during snowmelt. It is somewhat difficult to understand how such a process could achieve erosion of a depression in bedrock, particularly in view of the short time period involved.

The inspiration, in the case of both Derruau and Twidale as to nomenclature and the processes involved, came from features described by Boyé (1950) in Greenland, which he designated *ravins de gélivation.* These are ravine-like features with steep rock walls, and a flat, or slightly convex bottom. Their long profiles are irregular, and the material in the bottom of the channels consists of large blocks bedded in sand. The processes which Boyé considered to be responsible for these forms were gelivation for the widening of the *ravins,* and for the comminution of the rocky talus thus produced, and solifluction for the movement of the sands and gravel thus derived down the *ravins.*

Twidale (1956 ; 1958) was probably even more influenced in his discussion of the *vallons* on Dolly Ridge by Boyé's ideas than was Derruau. His theory of formation is basically the same as that of Derruau. As regards age, Twidale considered the *vallons* to be entirely post-glacial in origin, and claimed that there was no sign of striations or any other indication of glacial activity associated with the *vallons.* Even more significantly, he emphatically refutes any evidence of a meltwater origin :

> *« Il n'y a pas davantage de preuves que ceux-ci ont été érodés par des cours d'eau débouchant sur une masse de glace occupant la vallée de Knob Lake : la forme d'alcôve et l'inégale dénivellation des vallons au-dessus du fond de la vallée principale indiquent qu'il ne peut en être ainsi. »*

In his discussion of the *vallons,* Andrews (1961 ; 1963) stressed the lack of frost-shattering on the side-and head-walls. Temperature measurements at the rock/snow contact at the back of one of the *vallons* revealed a variation of only 1°C above and below the freezing point, which is not likely to produce any effective frost-shattering. Further, Andrews found the rock-walls to be well covered with crustaceous lichens, indicating little contemporary frost-action. He also refuted the possibility of the removal of the material by solifluction, in view of the lack of finer particles of the silt/clay fraction, and concluded that (Andrews, 1963, p. 141) :

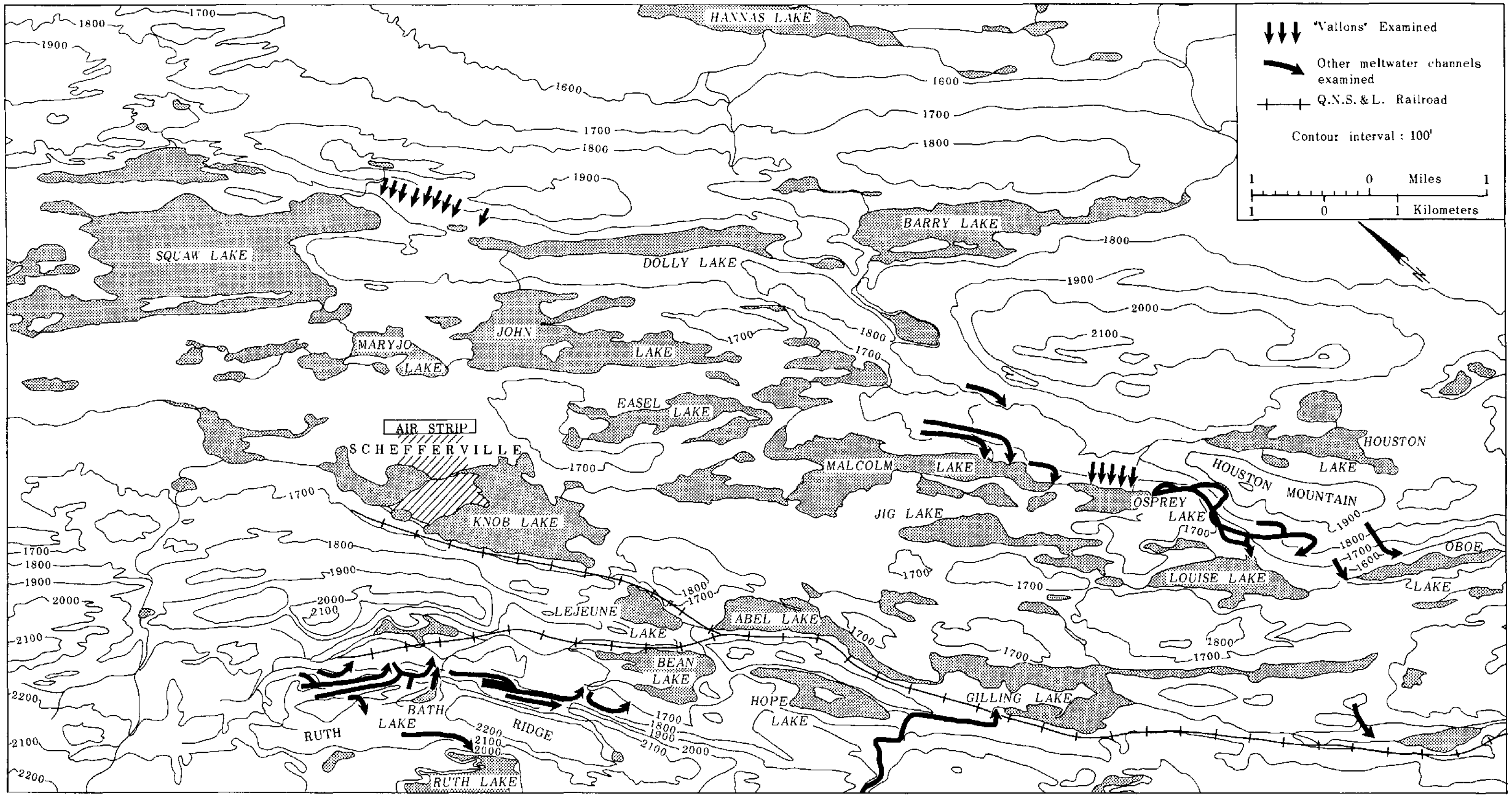
> « mechanical weathering in the Canadian sub-arctic and even in the arctic is a slow process, except under favourable conditions. It is stressed that oft-quoted effects of frost-action are rarely proved by adequate quantitative work. »

In lieu of the gelivation and solifluction hypothesis, Andrews postulated that the *vallons* were initially located along major joint lines, which had been widened by preglacial weathering processes. The major role, however, was played by glacial meltwater during the deglacierization of the area, some 6 000 years ago. The evidence for this hypothesis is substantial. Thus, at the northern end of the series of *vallons* on Dolly Ridge, a glacial drainage channel leads into one of the *vallons* which breaches the ridge ; and at the south end, a complex of small arcuate channels is closely associated with the most southerly of the *vallons.* Andrews' most conclusive evidence for the *vallons* having been largely shaped by glacial meltwaters was the discovery of a large block of Wishart quartzite lying at the outlet of one of the *vallons* ; the bedrock consists of Attikamagen slates and argillites. Since the slopes surrounding the erratic were too gentle for it to have rolled to its present position, Andrews concluded (1961, p. 7) that the boulder must therefore post-date the *vallon.* The only feasible explanation is the emplacement of the erratic from melting ice into the *vallon.* Andrews therefore considered the *vallons* to be structurally-controlled subglacial chutes, in which periglacial processes have produced slight modifications in the form of limited post-glacial frost-shattering and talus development.

Having examined the Dolly Ridge *vallons,* the author discovered numerous other examples of *vallons* in the Schefferville area. They included the group of five, mentioned earlier, near Osprey Lake, another *vallon* a short distance to the south near the north end of Oboe Lake, one on the north of Ruth Ridge, hanging above the Bath Lake depression, and a further one quite close to the Knob, at the north end of Lejeune Lake (see Figure 6). Incipient and poorly-developed forms were observed to be widespread.

Apart from the essential characteristics already mentioned, the *vallons* listed above have several significant features in common. Thus, despite varying bedrock-types, they are all excavated in rocks with a fairly steep northeasterly dip : the Dolly Ridge *vallons* are cut in slates and argillites, dipping northeast at an angle of 32-40° ; those at Osprey Lake are in slates dipping northeast at an angle of 50-58° ; while those on Ruth Ridge and at Lejeune Lake are in rocks of the Sokoman iron formation, with equally steep northeasterly dips. Moreover, all the *vallons* examined face west-southwest or southwest.

All the evidence from these other locations supports Andrews' theory for the formation of the *vallons.* Thus, in the case of the Ruth Ridge and Osprey Lake examples, a clearly marked meltwater channel leads along the strike, before turning at right angles down into the *vallons.* At Osprey Lake,



SELECTED FLUVIOGLACIAL EROSION FEATURES IN THE SCHEFFERVILLE AREA

Figure 6 *Distribution of « vallons » and other meltwater channels examined.*

this channel runs along just behind and above the headwalls of all five *vallons*, and its meltwaters appear to have flowed down the *vallons* in succession from south to north. However, as Andrews (1963, p. 142) has implied, it is equally feasible that several of the *vallons* operated simultaneously. It is significant that there are several closed bedrock depressions in the bottom of the strike channel just above the headwalls of some of the Osprey Lake *vallons* (Photo 8) ; they reach a depth of six feet, and it is quite inconceivable that such depressions could have been eroded and evacuated by any type of mass-movement.

At Lejeune Lake, the *vallon* is closely associated with two small arcuate channels a short distance to the south. It would appear that the meltwaters flowed down through the *vallon*, then through the arcuates in turn, or perhaps they were formed consecutively. A similar relationship occurs in the case of the Ruth Ridge example, where an arcuate channel begins just to the south of the mouth of the *vallon*.

In the bottoms of two of the Osprey Lake *vallons*, large erratics of the characteristic grey-green Denault dolomite, shot through with veins and nodules of chert were found (Photo 9). As Andrews deduced from a similar situation, this testifies to the fact that the *vallons* are clearly not postglacial in origin, since these erratics could only have arrived at their present positions by emplacement from an overlying ice cover.

Closed bedrock depressions in the bottoms of the *vallons* are quite common (Photo 10). It has already been stressed that mass movement processes appear quite inadequate to explain these depressions, and it is

Photo 8 *A closed bedrock depression in the bottom of the strike-aligned channel just above the headwall of one of the Osprey Lake « vallons ».*

Photo 9 *A large erratic of Denault dolomite lying in the bottom of one of the Osprey Lake « vallons ».*

Photo 10 *The Ruth-Ridge « vallon ». A closed depression lies beyond the bedrock step in the foreground.*

Photo 11 *Round water-worn cobbles in the closed depression at the foot of the headwall in the Ruth Ridge « vallon ».*

suggested that meltwater is the most likely agent of erosion. Conclusive proof of the meltwater origin of the *vallons* is found in the Ruth Ridge example ; at the bottom of the closed bedrock depression at the foot of the headwall, there is a deposit of large well-rounded water-worn cobbles of varying lithologies (Photo 11). This deposit is being encroached upon from all sides by the easily distinguishable blocky, angular talus of the Sokoman formation, derived as a result of postglacial frost action from the surrounding rock faces. This is a clear proof that the major factor in the formation of the *vallons* is meltwater erosion, while the contribution of postglacial periglacial activity is only one of slight modification.

In his discussion of the Dolly Ridge *vallons*, Twidale (1956) includes a description of arcuate depositional forms (*bourrelets arqués*), composed of coarse angular material. He considered them to have accumulated as a result of the movement of material by solifluction from the *vallons*. Andrews, as already mentioned, cast doubt on a solifluction origin, in view of the absence of fines, and suggested that these were fluvioglacial fans, comprising the material eroded from the *vallons* (Andrews, 1961, p. 7).

In the case of the Osprey Lake *vallons*, no new light is shed on this matter, as there is no sign of any deposition at the mouth of the *vallons*. Presumably, the meltwaters resumed an englacial course at this point, without any appreciable break in the gradient. However, on Ruth Ridge, there are extensive deposits which appear to be fluvioglacial in origin. They take the form of a hummocky area, consisting of partly sorted, partly rounded material, covering a large extent on either side of the Bath Lake depression, and fanning out from the mouth of the *vallon*.

Had the Ruth Ridge *vallon* been included in the earlier studies, it seems probable that the controversy as to their formation would not have arisen. It is particularly unfortunate that the earlier researches were restricted to *vallons* cut in the more easily weathered slates and argillites of the Attikamagen formation. Any sign of water-worn material in the bottoms of the Dolly Ridge *vallons* has probably been completely covered by postglacial talus formation. Indeed, it would be interesting to see whether excavation in the talus in the bottoms of the *vallons* might not bring such material to light. Identification of the materials of the *bourrelets arqués* has similarly been rendered more difficult by the lithology and weathering characteristics of the slates and argillites of which they are composed. These are undoubtedly fluvioglacial materials, deposited as the result of a slight check in velocity, where the meltwater streams became englacial once more ; however, any indication of rounding, at best minimal due to lithology, has been erased long ago by frost action on material of such a susceptible rock type. Further, any sorting has been destroyed by cryoturbation.

Moreover, the fact that the meltwater origin of the Ruth Ridge *vallon* and its associated deposits is still clearly apparent, is also largely a factor of lithology. Due to the competence of the rocks involved (mostly Sokoman ironstones), periglacial processes have been less effective. As a result, within the *vallon* talus accumulation has been slower, while beyond the mouth of the *vallon*, the identity of the fluvioglacial material is still apparent, due to the slower rate of comminution by frost-action.

One aspect of the *vallons* which has so far been inadequately explained, is the steep back-wall. If it were entirely fault-guided, as suggested by Andrews, one might reasonably expect the meltwaters to have exploited the fault more extensively, to produce a wide plunge-pool with a straight, steep back-wall, narrowing to a steep-sided channel below. There is in fact little sign in any of the *vallons* of a fault of the magnitude implied. As an alternative hypothesis, it is suggested that the critical factor is the dip of the rocks. In every case, this is towards the north-east, while all the *vallons* so far examined face towards the southwest or west-southwest. It is proposed that there is a direct relationship between these two facts.

In view of the relationship between the trend of the structure and topography and that of the ice-directed subglacial drainage during late-glacial time, already discussed, it seems quite probable that an englacial stream, impinging on the surface of a ridge, such as Ruth Ridge or Dolly Ridge, might flow along the strike for some distance, before flowing directly down one or other of the flanks of the ridge. If this flow were down the southwest flank, the meltwaters would inevitably be flowing down at right angles to the outcrops of successive beds, as a result of the persistent northeasterly dip observed at the sites of all the *vallons.* It is suggested that under such conditions, the plucking action of the water would be sufficient to create and maintain the steep headwall of the *vallon.* The so-called *vallons de gélivation* are thus produced by the headward retreat of a subglacial waterfall, the significant factor being the relationship between the direction of flow and the dip of the rocks.

If, on the other hand, the meltwaters turned eastwards, straight down the dip, a normal steeply-graded subglacial chute would be produced. This has happened at several points on the east face of Ruth Ridge, and the chutes which have been produced are in striking contrast to the *vallon* on the other side of the ridge.

If meltwater flow were sufficiently prolonged, the headward retreat of the subglacial waterfall responsible for the formation of a typical *vallon* should eventually produce a semi-graded channel right through the ridge into which the meltwater stream had incised itself, as described by Andrews (1961, p. 5), from Dolly Ridge. In the case of the Ruth Ridge *vallon*, headward retreat has progressed to such an extent, that the strike section of the channel was reached, and the fall had begun to retreat round the corner and northwards along this strike section. As the structure was clearly no longer conducive to the maintenance of a steep wall, the fall had already begun to degenerate, when the process was interrupted by the cessation of meltwater flow.

As a result of this survey of the *vallons* in the Schefferville area, the occurrence of features of this type, with its characteristic steep headwall can, to some extent, be predicted. They should occur only in areas where well-bedded rocks display a uniform high-angle dip, and where englacial and subglacial meltwater activity was intense. The final and essential requirement is that the meltwaters should have flowed downhill, in the opposite direction to the dip, across the outcropping ends of successive beds.

It is hoped that this examination of the *vallons* in the Schefferville area will to some extent meet the need mentioned by Andrews (Derbyshire, 1964, p. 923) for a complete survey of all *vallon*-type landforms in the area. It should be made clear, however, that the writer's terms of reference appear to differ somewhat from those of Derbyshire. Under the term *vallon*, the latter would include a wide variety of forms, including circular bedrock depressions and semi-ovoid hollows (Derbyshire, 1964, p. 923 ; Pl. 1). While the writer acknowledges the existence of numerous features of this type in the area, he wishes to retain the term *vallon* for rock-walled dry valleys cut into a hillside and characterized in particular by a steep headwall cut in bedrock.

Conclusions

During the penultimate stages of the disintegration of the late-Wisconsin ice sheet which covered the Quebec-Labrador Peninsula, large englacial meltwater streams flowed in a NNW-SSE direction across the area where the town of Schefferville is now located. These streams flowed at an unknown depth within the ice, but were limited as to their depth of penetration by ice conditions. Due to a very marked linear structure, controlled by closely spaced parallel folds and thrust-faults, there is a close correlation between structure and topography in the Schefferville area. It was to be expected, therefore, that when as a result of downwasting, the zone of meltwater penetration was sufficiently lowered to permit the meltwater streams to impinge on bedrock, very marked structural control of alignment of the resultant meltwater channels would be displayed. In the simplest cases, the meltwaters were guided in straight fault-guided and strike-guided channels, the strike of the rocks and the trend of the thrust-faults being generally fairly close to the direction of ice-directed meltwater drainage.

In the Houston Mountain area, however, successive impingements of an englacial stream on the projecting flank of a hillside composed of slates displaying steeply-pitching anticlinal folds, resulted in the unusual occurrence of the meltwaters being guided successively around the noses of three of these pitching anticlines. The result is a series of three very striking arcuate channels, unusual in that they were formed subglacially, and are entirely structurally controlled as to their form.

The writer is in agreement with Andrews (1961, 1963) as to the fluvioglacial origin of the features earlier interpreted as *vallons de gélivation.* These are a special type of structurally controlled subglacial chute, resulting where a meltwater stream flowed across steeply dipping sediments, in the opposite direction to the dip. The result was a subglacial waterfall, which as it retreated, maintained a steep head-wall, resulting in the formation of a *vallon.*

These are only two of the innumerable examples from the Schefferville area of structural control of meltwater drainage. The significance of structural control in the fluvioglacial landscape in this area can not be over-emphasized. Subglacial meltwater drainage, almost completely dominated in the details of form and alignment by structural features such as folds, faults and dykes, as exemplified in the field area, has been reported from no other area.

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ABSTRACT

The coincidence as to location of a late-Wisconsin ice disintegration centre. with an earlier ice dispersal centre, some 30 miles north-west of Schefferville, Quebec, resulted in large scale englacial meltwater flow from north-north-west to south-south-east across the Schefferville area. The direction of flow was controlled by the englacial hydraulic gradient, controlled in turn by the ice surface gradient. The Schefferville area is underlain by Proterozoic metasediments, exhibiting a series of parallel folds and thrust-faults aligned NW-SE ; this structure is reflected in the marked parallelism of the ridges and valleys. When the englacial meltwater streams were let down on to this substrate, structurally controlled alignment of the meltwater channels resulted. Generally, this has resulted in remarkably straight channels aligned along the strike or along faults. In the Houston Mountain area, however, steeply pitching anticlines in slates produced a striking series of subglacial arcuate channels. At several points in the Schefferville area, subglacial meltwater flow down a hillside at right angles to the strike, and in the opposite direction to the dip, in zones of steeply dipping, well-bedded sediments, has produced the features referred to in literature as *vallons,* and earlier explained as being largely periglacial in origin. These are a special type of structurally controlled subglacial chute, in which there has been only slight periglacial modification of the original fluvioglacial form.