67-52

GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES

PAPER 67-52

SURFICIAL GEOLOGY OF LA PATRIE— SHERBROOKE AREA, QUEBEC, INCLUDING EATON RIVER WATERSHED

(Report, 6 figures and P.S. Map 18-1967)

B. C. McDonald

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ROGER DUHAMEL, F.R.S.C.
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1969

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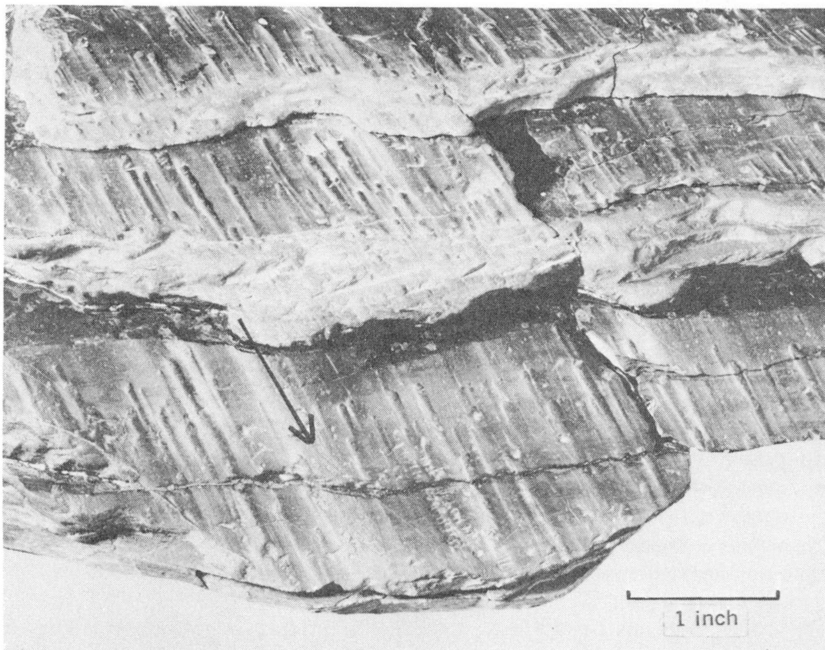
ABSTRACT

Exposures along major rivers reveal the presence of three till sheets, probably all of Wisconsin age, separated by lake sediments. Nonglacial episodes antedating the last glacial phase are widespread and are recorded by lake sediments in thirty sections within the map-area. Ice-flow during the last glacial phase was from the northwest. No evidence exists to support the concept of late glacial flow of ice into Quebec from New England. Till fabrics and indicators show that ice flowed from east-northeast during at least part of the penultimate glacial phase.

Ice-front positions during final deglaciation are well marked and indicate northwestward retreat of an active ice-front. Glacial lakes were dammed by the ice and were widespread during deglaciation. Principal areas of interest for groundwater potential are areas of ice-front sedimentation and drainage diversion.



Frontispiece (GSC No. 200156)
Crag-and-tail glacial striations on specimen collected from a horizontal bedrock surface 3 miles east of Lawrence. Tails of slate have been protected down-glacier by tiny pyrite cubes. Arrow shows sense of glacial movement (from N 45° W). Striations of this type are common in the map-area. The light-coloured bands are interstratified siltstone.

SURFICIAL GEOLOGY OF LA PATRIE – SHERBROOKE AREA, QUEBEC, INCLUDING EATON RIVER WATERSHED

INTRODUCTION

This is a preliminary report on Pleistocene geological mapping carried out during the 1966 field season in a 460-square mile area of southeastern Quebec. The area includes all of 21 E/5 E½ (Sherbrooke) and 21 E/6 W½ (La Patrie), and parts of 21 E/3 W½ (Malvina), 21 E/4 E½ (Coaticook), and 21 E/6 E½ (La Patrie) of the National Topographic System. The area is located between Sherbrooke and Mount Megantic and includes the settlements of East Angus, Cookshire, Sawyerville, St-Isidore-d'Auckland, Martinville, and La Patrie.

The main objectives were to provide background data for a project of the International Hydrological Decade undertaken in the Eaton River watershed by Quebec Department of Natural Resources, and to extend investigations of Quaternary history (McDonald, 1967a) eastward to the New Hampshire border.

Capable field assistance was provided by Roger D. Thomas, André J. R. G. Lemieux, and Roy E. McArthur. The co-operation and stimulating field discussions offered by officers of the Quebec Department of Natural Resources are gratefully acknowledged.

The Eaton River watershed, about 250 square miles in area, is flanked to the northeast by Salmon River basin and to the southwest by Ascot River basin. All three watersheds drain northwestward from the height of land at, or near, the International Boundary to the St. Francis River. Eaton River flows northwestward for about 27 miles and drops from an altitude of slightly over 2,000 feet at the International Boundary, to 600 feet at East Angus where it empties into the St. Francis River. Principal among tributaries to Eaton River are the North and Clifton Rivers. Longitudinal profiles of the major rivers are shown in Figures 1 and 2 (in pocket).

Northwest of St. Francis River, the map-area is underlain by bedrock, largely metavolcanic and granitic rocks of the Green Mountain anticlinorium. The anticlinorium is represented by a belt about 30 miles in width, of resistant igneous and metasedimentary rocks striking generally N 35° E. The rest of the map-area is underlain by slates, limestones, and greywackes of the lower Palaeozoic St. Francis Group. Bedrock geology of portions of the area is discussed by Cady (1960), Cooke (1950, 1957), and McGerrigle (1935). Rock units strike consistently northeastward and the rivers, for the most part, flow northwestward across strike.

PLEISTOCENE SEDIMENTS AND STRATIGRAPHY

The surficial distribution of sediments is shown on the geological map (in pocket), and their stratigraphic relationships in the major valleys are depicted on Figures 1 and 2 (in pocket).

Manuscript received September 5, 1967.

Generally, glacial drift is thickest in the valleys and thins toward the interfluves. Although in places the rivers flow on bedrock, drift thicknesses of as much as 200 feet have been measured locally. Because of irregularities in glacial and nonglacial terrestrial deposition and erosion, continuity of stratigraphy between exposures (and thus the potential of any unit as an aquifer) must be proven by detailed drilling and/or seismic work. Closely spaced exposures show that locally the units may vary abruptly in thickness and that stratified sediment units, especially those beneath till, are commonly discontinuous. Field and laboratory studies have shown that in this region grain-size distributions of tills and of the finer-grained lake sediments vary little over wide areas. Grain-size distributions of such coarser grained water-laid sediments as ice-contact stratified drift, outwash, and glacial-lake sand (map-units 3, 4, and 6) vary greatly both horizontally and vertically; this is due to rapidly changing energy conditions in the sedimentation environment. Because the drift has been derived from calcareous bedrock terrain, exposures of fresh drift are calcareous.

Figures 1 and 2 have been compiled from more than one hundred and twenty-five measured sections exposed in the river banks. One disadvantage of depicting stratigraphy using the method employed in these figures is that the line of section is subject to the river's position in the valley. Exposures occur in river banks thus the stratigraphy shown does not occupy a uniform position in the valley but rather it meanders, with the river, from one side of the valley to the other. This gives an artificial first impression of the true valley stratigraphy; a thicker and more complete stratigraphy may underlie the adjacent valley walls. Consideration of Figures 1 and 2 should be accompanied by careful examination of the geological map. The large gap in river stratigraphy between East Angus and Petit-Lac (cf. Fig. 1) results from the absence of valley-wall exposures in the river banks along the larger, lower portion of Eaton River where low gradient has allowed development of a broad modern alluvial plain. The widespread exposures in river valleys of stratified sediments beneath till, coupled with bedrock outcrops on the interfluves, suggests that modern streams commonly have reoccupied valleys that originated prior to the last glaciation.

Similarities of colour, texture, and compactness among sediments of different ages permit identification of older Pleistocene sediments only in stratigraphic section. Therefore, unless nearby exposures indicated otherwise (cf. Fig. 1, in the vicinity of Randboro), all Pleistocene sediments at the surface were assumed to be associated with the youngest glacial phase. Stratigraphic evidence for more than one glacial phase is exposed at section 8 (Fig. 2) on North River, and at sections 10 and 11 (Fig. 1) on Clifton River. McDonald (1967a) describes other sections which indicate that at least three glacial phases are represented in southeastern Quebec.

Sediments stratigraphically below surface till

Exposures of sediments stratigraphically below surface till are common in high sections along river banks but are rare elsewhere. Locations of thirty such exposures are shown on Map 18-1967, twenty-nine of these are represented on Figures 1 and 2. In addition, 2 feet of glacial-lake silt beneath 2 feet of till was exposed in the morainic belt about 2 miles south of Bury and may indicate local readvance.

Older tills, like the surface till, are grey (about 5Y 5/1, Munsell notation), compact, calcareous, and stony throughout. They are texturally identical to the surface till. At sections 8, 10, and 11 the tills are 15 to 20 feet thick and show no weathering. Two-dimensional till fabrics are shown (Fig. 5) for each of the tills in section 8. These may represent three separate glacial phases.

Stratified lake sediments comprising sand, silt, and/or clay, separate the till units and commonly are exposed beneath the surface till in river sections. Despite an intensive search, nowhere in the map-area were organic remains found in these sediments. The lake sediments are typically thinly and evenly stratified, but commonly are intensely deformed within 5 feet of an overlying till. Current structures, although not uncommon in the coarser-grained facies, are vague and only locally developed. Generally the current direction was up-valley, away from the associated glacier and opposite to the current direction in the present river. Sandy units contain only minor gravel lenses and generally coarsen upward or downward toward till in contact with it. Sandy units are mostly light buff but are locally cemented with red iron oxide (e.g., at section 25); coarser grained sands tend to be non-calcareous whereas finer grained sands with considerable admixed silt tend to be calcareous. The leached portions may reflect greater permeability to groundwater. Silt-clay units commonly are grey, calcareous, and show varve-like laminations. Although generally well sorted, they locally contain abundant debris in the form of isolated, striated stones and small till-like lenses, presumably rafted to the site in icebergs. Grey, calcareous concretions, developed secondarily, are abundant in some sections and absent in others. The concretions, usually disk-shaped, average one to two inches in diameter.

Rarely, silt-clay units beneath till are buff-grey, are leached of carbonate, and are extremely compact. At section 23 on Eaton River, a unit of 25 feet of non-calcareous lacustrine sandy silt underlies 25 feet of calcareous till; the silt is intensely contorted, very compact, and contains near-vertical joints. The grain-size distribution of this unit is shown in Figure 3. Except for the absence of organic matter, it is identical to a silt unit exposed 4 miles east of Lennoxville on Ascot River, where organic matter has been dated at >54,000 radiocarbon-years B. P. (Y-1683).

These stratified sand and silt-clay units are interpreted as glacial-lake sediments deposited in front of an advancing (or retreating) ice-margin. Because the last glaciers flowed up the valleys, advancing ice blocked normal river drainage and dammed glacial lakes. Sediments, issuing in large part from the glacier, were deposited in these lakes and subsequently were overridden by the ice which deposited till. Sandy lake sediments may have been deposited near the ice-front with silt-clay units being deposited in quieter, more distal parts of the lake. Leached and buried silts, such as those in section 23, suggest the existence of a period of exposure and weathering prior to subsequent overriding by glacier ice.

Surface till

Glacial till is widely distributed at the surface in the map-area. Areas shown on the map as bedrock (map-unit R) are in fact mostly covered with a thin till veneer, locally perhaps as thick as thirty feet. In these areas, however, there are numerous bedrock outcrops, and bedrock controls the relief and local drainage. Elsewhere, the thickness of the till blanket varies abruptly but generally is greatest in the valleys. The thickest exposed section of surface till measured 75 feet (at section 4 on North River, Fig. 2).

The till is oxidized to a buff colour and is leached of carbonate near the surface; depth of leaching and oxidation varies between 0 and about 20 feet. In fresh exposure it is grey (about 5Y 5/1) and calcareous. The till is characteristically compact and is crudely fissile. Pebbles in it are well striated and have been rounded and faceted by glacial abrasion.

Grain-size distributions for three surface till samples are shown in Figure 3. Samples 1 and 2 are representative of the typical surface till (map-unit 1) which also contains boulders up to an estimated 5 per cent of the till volume. Erratics as large as 23 x 20 x 17 feet are associated with the surface till. (The particular erratic noted would weigh about 800 tons and has been carried southeastward from its bedrock source by the glacier at least 12 miles). Boulders as large as 2 feet in diameter are common in surface till.

Numerous pebble counts from typical surface till indicate abundance of erratics derived from rocks of the Green Mountain anticlinorium to the northwest. The percentage of such erratics decreases southeastward across the map-area from 35 to 50 per cent in the vicinity of Cookshire and East Angus, to less than 15 per cent near the International Boundary. This trend is accompanied by a corresponding increase of slate, limestone, and greywacke pebbles derived from the St. Francis Group. Pyrite cubes, common in the bedrock, are also common in the till and have been oxidized to a reddish iron oxide powder near the ground surface.

A distinct subfacies of map-unit 1, designated 1a, is silt-clay till which occurs in the vicinity of East Angus and in the Eaton River valley upstream from Randboro. In both places, the fine-grained nature of the till has resulted from ice overriding lacustrine silt and clay and incorporating this material into the till. The grain-size distribution of the till at East Angus is shown in Figure 3 (sample 3). In the 30-foot high pit face at East Angus, the till, grey where fresh, is oxidized to buff-brown to about 5 feet, although oxidation penetrates down as much as 20 feet along vertical joints. The joints may be caused by shrinkage due to desiccation after excavation of the pit. The till is faintly calcareous at the ground surface but strongly calcareous below a depth of 5 feet. Stones are very rare in the till except in patches of stony till as much as 4 feet thick which locally cap the silt-clay till. Angular clasts, between 1/4 and 2 inches in diameter, of unconsolidated glacial-lake silt and clay make up about 50 per cent of the till. These completely disoriented clasts are distinctly and evenly laminated (probably varved in places). Surfaces of the clasts are commonly parallel to internal stratification. The clasts are in a structureless silt-clay matrix,

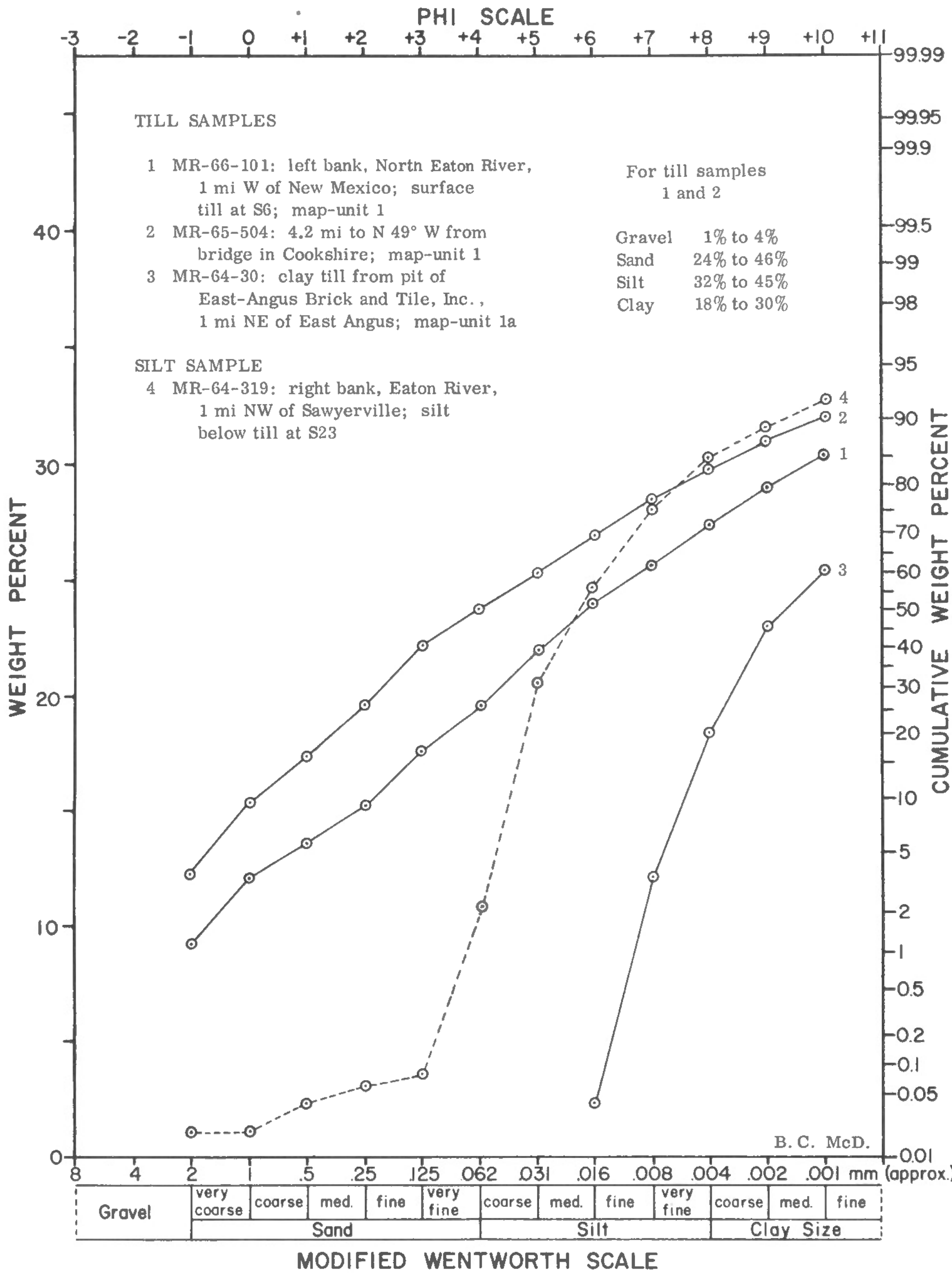


Figure 3. Grain-size distributions of three surface till samples and one buried silt sample (data are plotted on a form divised by Washburn and others, 1963)

probably derived from comminution of the lake sediment during the glacial reworking.[1] This till underlies a low, broad ridge which has several shallow, closed depressions; altitude of the ridge crest varies between 800 and 875 feet. The ridge trends northwestward across the St. Francis River valley and is breached by the river. Both the St. Francis River and Bury Brook have been sharply diverted by the deposit. The St. Francis River flows through a bedrock gorge at East Angus, suggesting that a buried channel of the river extends northeast under the ridge and has been plugged by the silt-clay till. The silt-clay till is well exposed in a pit 1.4 miles northeast of the bridge across the St. Francis River in East Angus. The till is exploited for brick material; bore-holes near the pit show that the material is at least 90 feet thick locally (R. Fortin, East Angus Brick and Tile Co., Inc., 1965, written communication).

A sequence of curved surfaces, continuous across a face 15 feet high and 30 feet from northeast to southwest, rise to the southwest and are gently concave-up. The surfaces are marked by zones a few inches thick of fine sand with highly contorted laminae, and are interpreted as shear zones formed near the terminus of glacier ice. The whole ridge of silt-clay till is interpreted as an end moraine built at the terminus of a glacier lobe which was advancing down the St. Francis valley from the northeast.

Ice-front positions in the present map-area are marked commonly by till ridges with intervening meltwater channels. These ridges, individually as high as 100 feet and as broad as half a mile, are shown on the map; they are prominent at East Angus, south of Bury, east and northeast of Island Brook, and northwest of La Patrie. From structures exposed in the moraines at East Angus, these till ridges are inferred to be, at least in part, shear moraines built near the termini of active glaciers. The compact, fissile, homogeneous nature of the sandy silty till which blankets the map-area, and the abundance of striated and faceted pebbles in this till indicate that it is a basal till deposited at the base of an active glacier. Strongly developed parallel pebble fabrics in this till (see discussion of Till fabrics pp. 11-15) support this inference.

Ablation till-gravel complex

A facies of the surface till, map-unit 2, underlies low, hummocky, constructional terrain. The till is loose, coarser grained than map-unit 1, and is closely associated with discontinuous lenses of silty gravel. Stones are commonly angular and little affected by glacial abrasion.

Small areas underlain by this material occur between Lawrence and Bury, about 3 miles east of Cookshire, and southwest of East Clifton. The close association

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[1] Two types of calcareous concretions are numerous in this silt-clay till: (1) Spheroidal concretions are present along joint planes in the pit face; thin sections show that these concretions are composed of cemented silt-clay till; and (2) Disk-shaped concretions are composed of cemented silt-clay with undeformed laminae. These may represent two generations of concretion formation (respectively post- and pre-deformation of the glacial-lake sediments) but further work in the pit would be necessary to establish whether or not disk-shaped concretions are forming now in association with single, large, undeformed clasts.

of this material and morainic belts leads to the suggestion that it is a product of melting out from blocks of stagnant ice near the glacier termini. The Bury-Lawrence mass may have resulted in part from isolation of an ice block down-glacier (southeast) from the edge of the Eaton River watershed.

Ice-contact stratified drift

Ice-contact stratified drift appears on the map as unit 3. Internal characteristics of stratified drift used to infer an ice-contact origin were (1) presence of till lenses; (2) large boulders in otherwise much finer grained gravel; (3) clasts of stratified sand or gravel, presumably transported and deposited while frozen; (4) rapid changes of grain size; (5) very angular sand grains, locally coated with silt; (6) deformation structures such as faults and folds readily ascribed to ice-push or to gravitational collapse as ice melted; and (7) stratification parallel to a hummocky topographic surface. Topography, areal distribution, relationship to direction of ice movement, internal structures, and direction of current-flow inferred from current structures were among criteria used to distinguish between different origins of ice-contact sand and gravel.

Current directions, determined from cross-stratification, were generally away from the glacier termini and thus were mostly in an up-valley direction. In contrast, ice-contact sand and gravel in the North River valley near its confluence with Sherman Brook display current directions to the northwest, toward the ice lobe in the lower Eaton and North River valleys. It is suggested that meltwater from the ice-front at Bury flowed down well-defined drainage channels along Sherman Brook carrying sediment which was deposited against the end of the ice tongue in the lowermost North River valley.

The most extensive ice-contact stratified drift deposits occur in zones or belts which have been interpreted in Figure 6 as ice-front positions. One prominent zone has been named the Stoke Mountain Interlobate Moraine after the Stoke Mountains at the north end of the moraine (McDonald, 1967a, p. 40). This is a ridge of ice-contact gravel and sand (as high as 200 feet, continuous for 12 miles, and with an average width of one mile) along the western edge of the map-area between St. Francis River and Martinville. The moraine rises from an altitude of 650 feet near the north end to over 1,000 feet near the south end. The crest west of Bulwer exceeds 1,075 feet, and the morainic material there is at least 200 feet thick. The south end of the moraine ends abruptly at Martinville; the north end grades into kame terraces capped by glacial-lake silts in the St. Francis River valley. Knob-and-kettle topography with some kettle lakes is a common feature of the moraine. Locally superposed on this topography are well-defined eskers in which the direction of current-flow was southerly, parallel to the moraine. Gravel pits in the moraine expose abundant ice-contact features. Locally, till-like lenses suggest slump of unsorted material from an adjacent ice-mass. Boulders more than 5 feet in diameter occur throughout. A 40-foot pit face at Sand Hill clearly exposes many internal features typical of the moraine. Coarse ice-contact stratified drift showing no unique current direction underlies strongly current-stratified gravel deposited by a south-flowing current. Caliche (calcrete) occurs below a leached zone at the surface containing limestone relics.

Greenish granite stones occur throughout the moraine south of the granite outcrop area at Ascot Corner, indicating southward transport of material. Among numerous 4- to 8-foot boulders on the pit floor are many Stanstead-type grey granites derived from the northeast and many red siltstone, volcanic, and greenish granite indicators from the northwest. A progressive decrease of resistant rocks, derived from the Green Mountain anticlinorium, from north to south in the moraine is accompanied by progressive southward dilution by calcareous and argillaceous rocks of the St. Francis Group, thus quality of gravel for exploitation decreases from north to south. This lithologic change along the moraine is additional evidence for a net southward transport of material during formation of the moraine. McDonald (1967a) has concluded that as the Stoke Mountains emerged from beneath the wasting ice-sheet, the ice was divided into two lobes. The moraine was built sub-aerially in the recess between the two lobes, as this recess migrated northward during deglaciation.

A second prominent zone of ice-contact stratified drift occurs between Bury, Cookshire, and the Stoke Mountain Interlobate Moraine at Sand Hill. Its configuration indicates that a glacier tongue extended about 4 miles southeastward up the Eaton River valley. Throughout much of this belt, particularly between Cookshire and Sand Hill, the sediment was deposited in a glacial lake abutting the ice-front. The topography is subdued and the material is progressively finer grained, better sorted, and better stratified upward in the deposit. The thickness of gravel in this zone is not known; gravel pits show thicknesses of as much as 30 feet but only rarely does the floor of the pit reach the base of the gravel.

A third zone occurs between Lawrence and Maple Leaf and outlines a glacier lobe that protruded about 5 miles up North River valley. Two smaller areas of morainic ice-contact sand and gravel occur in the upper reaches of Eaton River valley, at and near the International Boundary.

Extensive deposits of ice-contact sand and gravel occur on both sides of Salmon River valley at and north of La Patrie. These outline a glacier lobe that extended southward along the valley to La Patrie. This ice-margin position has been traced around the northwest flank of Mount Megantic.

Three small eskers exist singly in the map-area. All are narrow and none is higher than about 50 feet. A discontinuous esker system 4 miles long occurs west of Jordan Hill; a two-mile long esker occurs east of St-Malo; and a one-mile long esker occurs southwest of East Angus.

Outwash

Outwash sediments are stream deposited; they comprise sand and gravel and are derived more or less directly from the ice but are not characterized by ice-contact structures. Development of an outwash train requires dry land at the glacier terminus – a requirement that was not commonly met during deglaciation of south-eastern Quebec. Normal stream flow there is northwestward and because the retreating ice-margin prevented early establishment of such drainage, proglacial lakes were ponded against the ice-margin. Only rarely was the ice-front retreating up a slope and above lake level.

The only outwash mapped in the area is a body of pebbly gravel in the valley bottom west of St-Malo. It was deposited by meltwater flowing southward into Halls Stream and thence to the Connecticut River system.

Glacial-lake sediments

Because the ice-front, during retreat northwestward, continued to block normal stream drainage, proglacial lakes were present southeast of the ice-front during deglaciation. Lake levels dropped as lower outlets were uncovered during retreat of the ice-front, with the result that individual lakes were short-lived. The lake sediments have a patchy distribution. Commonly they abut moraines on the down-glacier side.

Sand-gravel facies

Large areas are underlain by glacial-lake sand and gravel (map-unit 6) west of Cookshire and in the vicinity of St-Mathias. This sediment is characterized by (1) a predominance of medium- to fine-grained buff sand; (2) even, well-developed stratification; and (3) local interstratification with lake silt and clay. Locally, the presence of large-scale foreset and topset stratification underlying a nearly horizontal surface indicates the presence of a delta; deltas of both ice-contact and normal fluvial origin are shown on the map (in pocket). Pebbly gravel is a minor part of this map-unit and commonly reflects a near-ice or near-shore sedimentary environment. With the exception of deltaic areas, the sand blanket probably averages less than 10 feet in thickness. The paucity of well developed near-shore features suggests that most of the glacial-lake phases were short-lived.

Silt-clay facies

The silt-clay facies (map-unit 5) is not widespread at the surface. It is silt-rich and typically well laminated, but in some exposures lamination is vague or absent. Grey and calcareous where fresh, the silt-clay facies becomes light buff to reddish-brown where oxidized. Ice-rafted stones are common in this unit.

The varved nature of rhythmically laminated silt sequences is inferred both from a gradual colour change from buff in the oxidized summer layer to grey in the winter layer, and from coarser grained summer layers grading upward into finer grained winter layers. The colour change is thought to result from differential permeability, resulting in preferential oxidation, by groundwater, of the coarser grained layers. The regular gradations of both grain-size and colour within a sharply bounded couplet were accepted as evidence that each couplet was deposited in one year. Calcareous concretions occur in the summer layers of some varves.

River-terrace sand and gravel

River-terrace sand and gravel (map-unit 7) occur along the principal rivers in the map-area where they underlie terraces as high as 157 feet above the present river (cf. section 5, Fig. 2). These sediments are current stratified and were deposited by streams flowing in the same direction as those now occupying the valleys. Pebbles are well rounded and typically less than 3 inches in diameter, although locally the sediment is cobble and boulder gravel. River terraces generally are not extensive. They occur mostly within about 50 feet of present stream level and indicate post-glacial down-cutting by the rivers. River gravels as thick as 30 feet have been measured.

Swamp sediments

Peat deposits (map-unit 8) thicker than 3 feet are rare in the map-area. The most extensive peat deposit is in the 'Johnville bog' adjacent to the Stoke Mountain Interlobate Moraine, 4 miles southwest of Birchton where the peat is several feet thick. The bog occupies a depression that probably formed by the melting of a residual ice block soon after formation of the moraine.

Modern alluvium

Modern alluvium (map-unit 9) is present in all stream valleys but is extensive only along major rivers. It consists of all gradations between silt and boulder gravel and it commonly contains modern plant fragments. Terraces underlain by modern alluvium are numerous up to about 12 feet above present stream level.

Modern alluvial plains are locally broad and well developed along the North and lower Eaton Rivers. Their width ranges abruptly from 0 to $\frac{1}{2}$ mile. It is possible that the broadness of the alluvial plain is related to a relatively long-lived up-valley extension of a glacier tongue. It is also possible that alluvial plains broaden where easily eroded materials occupy channels that existed prior to glacier advance, and narrow where they have been post-glacially superposed on more resistant materials which may not be in the former channel. Thus the distribution of modern alluvium could assist the search for buried channels.

DIRECTIONS OF ICE MOVEMENT

Whether or not ice flowed into Quebec from late-glacial centres of outflow in Vermont, New Hampshire, and western Maine has been a subject of controversy since 1887. The background of this discussion was summarized by Flint (1951) and, more recently, by McDonald (1967a). McDonald concluded that misinterpretation of striations and of distribution of surface erratics had augmented the controversy. He demonstrated that during the last glacial phase, ice flowed from the northwest across southeastern Quebec to the International Boundary and that there was no evidence to support the concept of late-glacial flow northward into Quebec from New England. Evidence was presented to show that during the early part of the penultimate glacial phase, ice had flowed from about N 80° E across southeastern Quebec. New evidence collected during the 1966 field season, partly in the present map-area, strongly supports these conclusions. Criteria used are striations, fluted surfaces, till fabrics, and indicator lithologies.

Striations and fluted surfaces

Too often striations are assigned unique directions on the basis of inferences from other data. The sense of movement should be indicated by an arrowhead only for those striations that indicate a unique direction. In most cases it is very difficult to assign relative ages to striations, whether they be isolated or in intersecting sets. The subjective criterion commonly used is the relative apparent freshness – a characteristic determined by many factors, of which time is only one. Effects of local topography, configuration of the ice-front, and variations of direction of surface slope on the glacier result in striations with different directions being formed at the same time at different sites, or at slightly different times at the same site. Distinction between such relatively insignificant variations and variations having temporal and regional importance, is commonly subjective. Striations at the surface were made largely during the last glacial episode and are thus of limited use in reconstructing earlier Pleistocene ice movements.

Glacial striations are abundant in the map-area and indicate that during the last glacial phase, ice flowed from northwest to southeast. All striations were measured on horizontal or nearly horizontal surfaces and, as far as possible, on local heights of land. Most sites represent the average direction of several striations, which rarely vary as much as 30 degrees on a single exposure. All arrowheads were based on crag-and-tail features that were up to a few inches long and associated with the striation. At some sites a striated quartz vein 1 inch to 2 inches wide had protected a tail of weaker rock downglacier from it. More commonly, tails of slate have been protected downglacier from tiny pyrite cubes (Frontispiece). Crag-and-tail striations within half a mile of the International Boundary indicate ice movement toward southeast. Only at about 1 site in 15 was it possible to determine the sense of movement; all such striations consistently indicate ice movement from northwest to southeast. Striation trends in the major valleys suggest that late-glacial flow was controlled in part by topography.

Fluted surfaces are consistent with movement directions indicated by striations. Individual flutes are as long as 1.7 miles and up to 20 feet in relief. Some fluted surfaces are ribbed tails starting at bedrock knobs, thus allowing determination of the sense of ice movement. The flutes appear to be shaped entirely from till; an exception is the fluted area 4 miles south of East Angus, where bedrock shallowly underlies the surface.

Till fabrics

Although till fabrics present problems in interpretation (McDonald, 1967a, pp. 77-8) they are a useful means of investigating the direction of ice flow during till deposition. The method can be applied equally well to multiple tills in stratigraphic section. Twenty two-dimensional till fabrics have been measured in surface till and are shown on the geological map (in pocket); two of these, measured in three dimensions, are shown in Figure 4. Fabrics were measured also in each of the three tills at section 8 (Fig. 5). Briefly, till fabrics are interpreted largely on the premise that elongate pebbles at the base of a glacier tend to be oriented parallel to direction

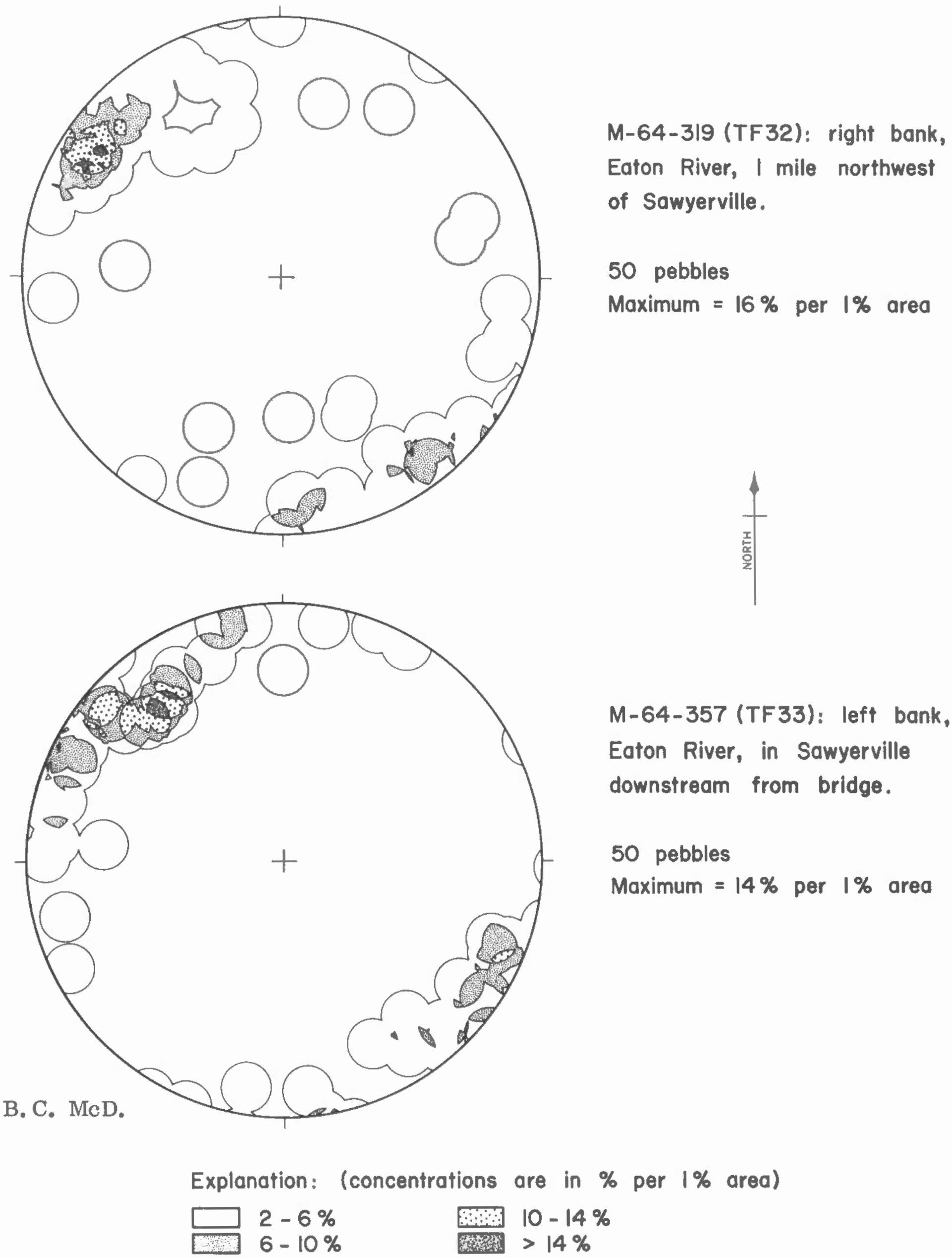

Figure 4. Three dimensional till fabrics from surface till near Sawyerville on Eaton River (see Fig. 6 for location)

of ice movement (sometimes they are at 90 degrees, or transverse, to movement) with their long axes plunging upstream. Thus, two-dimensional fabrics give a line but no arrow; three-dimensional fabrics suggest the sense of ice movement.

Method of measurement

All fabrics were measured in compact tills, presumably of lodgment, or basal, origin. Fabrics were taken from below the soil zone, at depths greater than 1 foot and commonly greater than 3 feet below the surrounding land surface. Sites where material showed any sign of disturbance were avoided. A thickness of about 1 foot of compact material was excavated from each exposed vertical face before fabric measurement was begun. Fabrics were measured only where the local slope of the ground surface was less than 2 degrees, and slope directions were noted to check that the fabric maxima were not obviously related to possible slope movements. Each stone was carefully excavated with a trowel or knife and was measured in situ with a Brunton compass; orientations were recorded in a notebook. An attempt was made to avoid bias by not plotting the number of stones in particular azimuthal groups until after all stones were measured.

All stones measured had axial ratios of a:b ≥3:2 and b:c ≥3:2, where a, b, and c are major, intermediate, and minor axes respectively, and are mutually perpendicular. Almost all clasts present in the till were within these shape restrictions. In most cases, a:b was greater than 2:1. Most a-axes measured were between $\frac{1}{2}$ inch and 2 inches long. Where possible, stones with c-axes nearly vertical were selected. However, rare stones with b-axes vertical were included with some of the fabrics and were found to be evenly distributed around the maximum determined from other stones.

Plunges of a-axes were measured by first removing a stone from the till and leaving a well-defined mold of finer grained material outlining the exact shape of the stone. This permitted examination of the stone to see the a-axis. Then a 7-inch aluminum knitting needle was pushed into the mold in the orientation of the a-axis of the pebble, and the plunge of the knitting needle was measured with a Brunton compass. Orientations of a-axes measured in three dimensions were plotted on the lower hemisphere of an equiareal stereographic net and concentrations of points were contoured.

Results

Maxima of all fabrics from surface till, with the exception of fabrics 14, 15, and 21, are aligned northwestward, parallel to direction of ice movement indicated by striations. Fabric 23 is not well developed. West of Cookshire, individual fabrics within two fabric pairs (14 and 35, and 15 and 34) are at right angles to each other. This illustrates the complexity of till fabric interpretation but also may reflect complexity of the local geology. Proximity of the Stoke Mountain Interlobate Moraine suggests that late-glacial ice in this part of the map-area was flowing at one time from northeast toward the moraine. However, nearby striations, and the orientation of the Sand Hill-Cookshire moraine segment there, indicate movement from the northwest, perhaps at a slightly different time in the deglaciation. Thus both sets of fabrics may

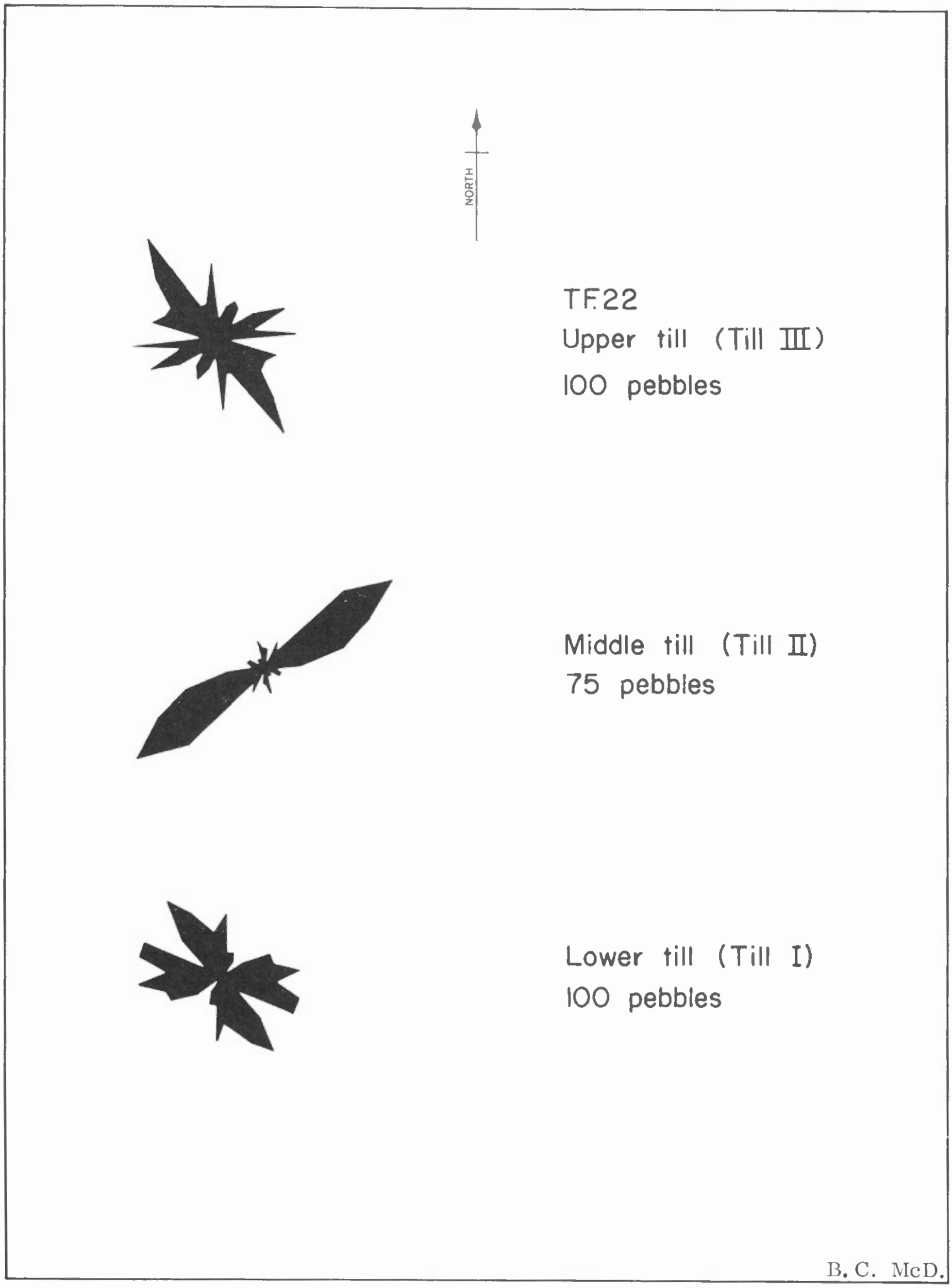

Figure 5. Till fabrics from section 8 on North Eaton River

be parallel, although this does not seem likely. Fabric 21 is probably transverse, in view of the orientation of the nearby moraines and of striations only 1.4 miles away.

Three-dimensional fabrics near Sawyerville (Fig. 4) show that the maxima of long axes orientations plunge northwestward. This supports other evidence that ice flow was toward southeast.

The three tills in section 8 may represent the three separate glacial phases discussed by McDonald (1967a). If so, they suggest (Fig. 5) that at times during the first and last phases ice flowed from northwest, but at sometime during glacial phase II ice flowed from northeast. (Northeast is specified because of evidence presented by McDonald (1967a), and also because of lithologic evidence given in the next section of this report).

Indicator lithologies

Most rock types in southeastern Quebec occur in formations which are continuous and similar for several miles along a general strike of N 35° E. Such rocks are useful as indicators when related to a particular ice-movement direction; otherwise the source area can seldom be defined within 180 degrees. Rocks from the Green Mountain anticlinorium are sufficiently distinct from rocks of the St. Francis Group that they provide good general indicators when related to striation and till fabric data. The general decrease, which has been noted, of Green Mountain lithologies from 35 to 50 per cent in the northwest part of the map-area to less than 15 per cent near the International Boundary is accepted as strong evidence supporting general ice flow from northwest during the last glacial phase. This conclusion is supported by numerous individual lithologic and mineralogic indicator trains detailed by McDonald (1966a, and 1967a, pp. 83-91).

'Point' sources of regionally unique and easily recognized lithologies are rare in southeastern Quebec but permit definition of highly specific indicator trains. A ring of greenish augite syenite (nordmarkite), about 4 miles in diameter, which surrounds the Mount Megantic granite (cf. Reid, 1960) provides such a source. It is between 5 and 10 miles northeast of La Patrie. The coarse-grained syenite is easily recognized; it weathers to distinctive brown and white colours, and is green on a fresh surface due to its high content of green orthoclase microperthite. A strongly developed train of boulders, which are larger than 3 feet in diameter, trails southeastward from Mount Megantic, indicating final glacial movement toward the southeast. The percentage of nordmarkite boulders in the train decreases southeastward from about 45 per cent near the mountain to between 15 and 20 per cent at a distance of 10 miles. The northeastern edge of the train is sharply defined; an intensive search around the north and northwestern edges of the mountain revealed no clasts of nordmarkite. The southeastern edge of the train, although also rather sharply defined, is slightly 'fuzzy' due to the existence in the map-area of rare nordmarkite boulders (see Map 18-1967). The boulder 3.3 miles east of Island Brook is triangular in plan, measuring 24 x 23 x 19 feet, and is 7 feet thick. Nordmarkite boulders about 4 feet in diameter are present, but rare, along Ascot River about 5 miles west of the map-area. These boulders are 30 miles west-southwest of the source. The distribution of all the nordmarkite boulders southwest of Mount Megantic is bounded by a line trending S 70° W from the nordmarkite outcrop area. It is suggested that the boulders were carried into the map-area during the early part of the penultimate glacial phase when ice flowed from about N 80° E. Some may have been shifted slightly southeastward during the final glacial phase.

GLACIAL HISTORY

Glacial and nonglacial episodes antedating last glacial phase

Glacial episodes antedating the last glacial phase are recorded in the map-area in sections 8, 10, and 11. Tills in similar stratigraphic position are exposed commonly along the Ascot, Moe, and Coaticook Rivers southwest and west of Eaton River watershed. Radiocarbon dates of >54,000 B. P. (Y-1683) and >41,500 B. P. (GSC-507) (McDonald, 1967c), plus the pollen record in silt along the Ascot River (Terasmae, 1965) suggest to the author that the nonglacial interval between glacial phases I and II may correlate with the St. Pierre Interstadial. The leached silt at section 23 may record a time of subaerial weathering during this nonglacial episode.

From till fabric data in section 8 (Fig. 5), and from data presented by McDonald (1967a), it is suggested that ice during at least part of glacial phase I flowed from northwest and that ice during part of glacial phase II flowed from east-northeast. The east-northeast flow direction during glacial phase II is strongly supported by the presence in the map-area of rare, but large, nordmarkite boulders derived from Mount Megantic. Because this flow direction has been traced for more than 30 miles and is unrelated to topography imposed by bedrock structure, it may reflect the existence, in early post-St. Pierre time, of a centre of glacier outflow to the east-northeast.

Nonglacial episodes antedating the last glacial phase are recorded, mostly by glacial-lake sediments, in thirty sections in the map-area. As glaciers advanced into the area, ice interrupted normal stream drainage and lakes were dammed in the valleys. Sediments deposited in these lakes were overridden by advancing ice. The age of the nonglacial sediments immediately underlying the surface till is unknown. Two alternatives exist regarding their relationship to the surface till: (1) they represent a layer which is stratigraphically continuous beneath the surface till throughout the region. Thus they would mark a significant nonglacial episode and would antedate a major ice advance which may have continued across New England; or (2) they occur only locally where short forward pulses of a generally retreating ice-front overrode proglacial-lake sediments. The first alternative is favoured for the following reasons: (a) radiocarbon dates from coastal Maine and from the St. Lawrence Lowland indicate that final retreat of the ice-front across this 150- to 200-mile distance occurred in a very few hundreds of years. The rapid rate of retreat necessary, even allowing for widespread stagnation over northwestern Maine, renders unlikely the concept of many or extensive forward pulses; and (b) thicknesses of as much as 75 feet of compact surface till (cf. section 4) over lake sediments seem too great to be deposited during a rapid forward pulse. Thus it seems more likely that the surface till records a major ice advance and that the underlying lake sediments may be at least as old as 20,000 radiocarbon-years B. P.

The extent of glacier retreat prior to final glacier advance is unknown. If the silts dated at >54,000 and >41,500 radiocarbon-years B. P. correlate with the St. Pierre peat of the St. Lawrence Lowlands, then the Gentilly Till (Gadd, 1960) would be equivalent to the tills of the last two glacial phases in the present map-area. This would imply that northwestward retreat prior to the last glacial phase did not reach the St. Lawrence River. Retreat may have stopped along the northwest flank of the Appalachian highlands, thus continually damming lakes in the present map-area and preventing lengthy exposure of lake sediments to subaerial weathering, at the same time maintaining an environment too harsh for rapid migration of plants into the area.

Last glacial phase and deglaciation

Ice of the final glacial phase flowed from northwest to southeast across the map-area. Topography exerted a strong influence on local flow directions during final retreat of this ice. Flow perpendicular to the lobate ice-margins shown in Figure 6 would have been diverse but short-lived. Striations in the larger river valleys are parallel with the valleys and are locally at angles of 45 degrees to regional ice-flow directions. Intersecting striations 3 miles east-southeast of Bury show the bottoms of crag-and-tail grooves (showing flow toward S 40° E) striated by a weak later set trending S 75° E. The later set is interpreted as a short-lived flow direction perpendicular to a nearby ice-front. Late-glacial ice flow almost at right angles to regional flow during the glacial maximum occurred between the Stoke Mountain Interlobate Moraine and the moraines at East Angus. There, a lobe that was diverted around Stoke Mountains flowed southwestward toward the moraines. The front of this lobe retreated northeastward up the St. Francis River valley, building the moraines at East Angus during a short readvance in the general recession.

Individual moraine systems, in places weakly developed, are marked by belts of ice-contact gravel and ridges of till, as well as by systems of ice-marginal drainage channels. Local details of proglacial lake levels at the ice-front are useful in placing the ice-margin with respect to lake outlets which must have been operative at the particular time. Correlation of ice-front positions between the Eaton River watershed and the Salmon River basin (Fig. 6) has not been attempted. The lake sequences in the Salmon River basin are not well known so altitudes of the moraine systems would be the only control. On this basis, the ice-front at La Patrie may best correlate with the small moraines near the International Boundary in the upper part of the Eaton River valley.

The existence of ice-front positions that are traceable across much of the map-area indicates that deglaciation was accomplished by backwasting of an active ice-front. Shear structures in the moraine at East Angus, together with evidence of local readvance with incorporation of proglacial lake silts into the till, supports this suggestion. Only locally in areas of ablation till - gravel sediments, is there evidence that blocks of ice stagnated. Compact till is a common sediment at the surface. This is in sharp contrast to terrain immediately south of the International Boundary, especially in Maine, where a predominance of ice-contact gravel attests to widespread stagnation of ice. It is suggested that downglacier from the water divide (largely coincident with the International Boundary) ice became cut off from the supporting flow

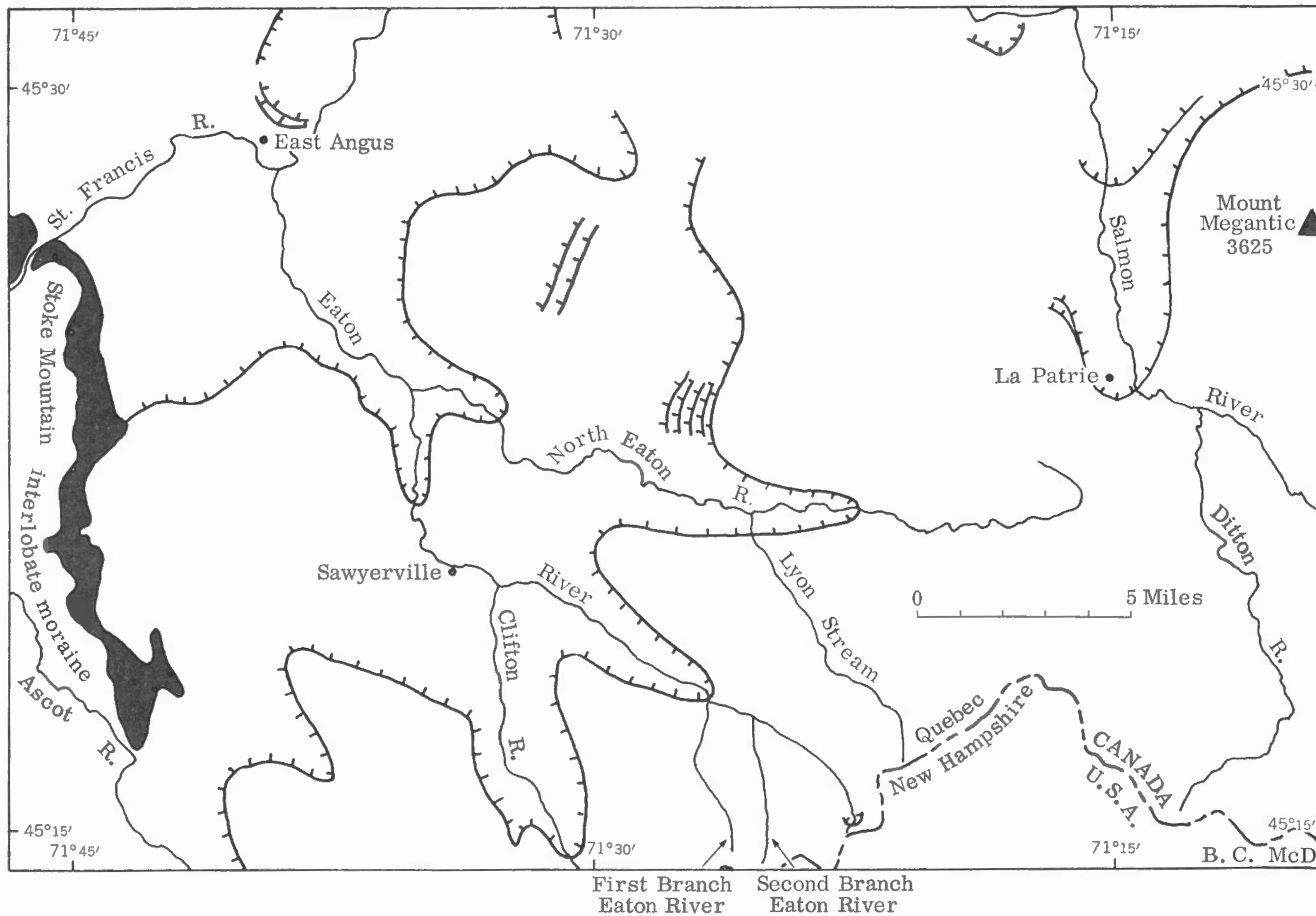

Figure 6. Ice-front positions in the LaPatrie - Sherbrooke area (hachures are toward the ice)

and stagnated, but that in Quebec deglaciation continued by backwasting of an active ice-front. Radiocarbon dates in Quebec and Maine indicate that deglaciation of the present map-area was accomplished rapidly, sometime between 12,600 and 13,000 radiocarbon-years B. P.

Proglacial lakes were dammed southeast of the ice-front during deglaciation. As ice recession continued, successively lower outlets were uncovered and lake levels dropped. Early drainage in each valley was directly south across the International Boundary into south-flowing stream systems. As recession continued, drainage flowed more southwestward through lower spillways. Lake levels in each valley then would have been controlled by the lowest col on the interfluve adjacent to the west. Two outlets south of the map-area allowed eventual escape of pounded water into south-flowing streams in New England. The higher of these now-abandoned spillways is at 1,400 to 1,425 feet altitude at the headwaters of Ascot River, 3 miles southwest of St-Malo. The second, lower, spillway is in Vermont at the head of the Coaticook River system.

ECONOMIC GEOLOGY

Sediment units with groundwater potential due to their relatively higher permeability are shown as map-units 2, 3, 4, 6, 7, and 9. Silt admixed and interstratified with sand and gravel locally lower the permeability of units 2, 6, and 9. Morainic areas offer extensive and locally thick deposits of lake sand and ice-contact sand and gravel. Gravel of the Stoke Mountain Interlobate Moraine is at least 200 feet thick west of Jordan Hill and locally is being exploited for groundwater. The morainic belt between Sand Hill, Cookshire, and Bury contains much coarse gravel and sand. Exposures of gravel at least 40 feet thick are common near Bury but the maximum thickness there is unknown.

Zones of ice-front sediment (Fig. 6) have groundwater potential not only by virtue of locally extensive permeable sediments at the surface, but also because these are commonly areas where minor glacier readvance has deposited till over proglacial sand and gravel. These buried sediments could be good aquifers. Areas where buried stratified sediments are exposed beneath till along river valleys are shown in Figures 1 and 2 (in pocket).

Other possible sources of groundwater are provided by buried channel segments in larger valleys. Glaciation has locally deranged much of the drainage network. Extensive areas of bedrock outcrop and steep gradient downstream from broad modern alluvial plains may indicate places where the present channel does not occupy the former stream course. The deepest part of the valley may lie buried under the valley wall and, if occupied by gravel or sand, could be a potential aquifer. Thus, communities such as Sawyerville, founded where waterfalls provide a source of power, may be situated also near potential sources of groundwater. A striking example of drainage diversion in the map-area is at East Angus where the clay-silt till moraine has displaced the St. Francis River 2 miles southeastward where it now flows partly in a bedrock channel. Bury Brook flows northeast around the moraine before entering the St. Francis River and flowing southwest. The stream derangement near East Angus has caused the lowermost Eaton River to flow in bedrock; this could be because effective base-level of the Eaton River was lowered by displacement of the St. Francis, or perhaps an abandoned channel of the lower Eaton River lies buried under the adjacent valley side.

Glacial-lake clay and silt that has been reworked into till is being exploited in the moraine at East Angus by East Angus Brick and Tile Co., Inc. Generally, clay and silt of map-unit 6 contains a high percentage of finely ground quartz. Near East Angus, however, ice flowing along the bedrock strike may have locally produced a clay-silt sediment with a high percentage of clay minerals derived from underlying Palaeozoic shales; the clay minerals in this sediment were not diluted by crushed quartz from adjacent formations.

Free gold in the surface till has been described by McDonald (1966a). It has not been found in economic quantity.

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