VERMONT GEOLOGY

OCTOBER 1985 VOLUME 4

GUIDEBOOK 1

CONTENTS

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VERMONT GEOLOGICAL SOCIETY, INC.

FOREWORD

About the Guidebook

Guidebook 1, the first of several such volumes which the Society plans to publish in the Vermont Geology series, contains guides of field trips the Society has sponsored in its 11 year history. Because the Society has not consistently required formal guides for past field trips, individual guides will appear in the order in which they are submitted. Each guide has the date of the original field trip on the first page. Guide C, Stratigraphy and Structure of the Camels Hump Group in North-Central Vermont by Barry Doolan, will be published in another issue; field work is still going on in his area and the author prefers to include these results. In this connection, it should be noted that although each field trip guide has been updated at the time of publication, it may not be definitive if additional field work is completed in the area.

Credits

The editor is indebted to the University of Vermont Department of Physics for use of its photocopy machine in the preparation of photo-ready copy. Thanks to Shelly Snyder for assistance with typing. Jeanne Detenbeck prepared the copy camera-ready for printing.

About the Society

The Vermont Geological Society was founded in 1974 for the purpose of:

1) advancing the science and profession of geology and its related branches by encouraging education, research and service through the holding of meetings, maintaining communications, and providing a common union of its members;
2) contributing to the public education of the geology of Vermont and promoting the proper use and protection of its natural resources; and
3) advancing the professional conduct of those engaged in the collection, interpretation and use of geologic data.

For more information about Society membership, meetings, and publications write to: Secretary, Vermont Geological Society, Box 304, Montpelier, VT 05602.

Officers 1984-1985

Additional copies

Additional copies of Guidebook 1 (Vermont Geology, Volume 4) may be obtained for $10.00 postpaid from: Treasurer, Vermont Geological Society, Box 304, Montpelier, VT 05602. Single copies of individual field trip guides are available at the following rates: A - $3.50, B - $1.50, D - $2.00, E - $3.00.

Please include a check payable to: Vermont Geological Society.

August 11-12, 1984

THETFORD MINES AREA, P.Q.

VERMONT GEOLOGY VOLUME 4

Brewster Baldwin, Middlebury College
Roger Laurent, Université Laval
Barry Doolan, University of Vermont

VGS GUIDEBOOK 1

FIELD TRIP GUIDE A

* Key Stops - don't miss these.

VERMONT GEOLOGICAL SOCIETY
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THETFORD MINES AREA, P. Q.

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INTRODUCTION

A belt of ophiolite, including chromite and asbestos deposits, extends through the northern Appalachians, and it is very well displayed in the Thetford Mines complex, 50 miles (80 km) south of Quebec City. The name "ophiolite" refers to a serpent-like aspect (**ophios** is Greek for serpent); the green color of the serpentine and the criss-crossed veins of asbestos give a scaly snake-like appearance that is common in serpentinized peridotite. Geologically, ophiolite refers to an assemblage of ultramafic rocks (dunites, peridotites), mafic rocks (gabbros, basalts), and overlying ocean-floor sediments.

This belt continues south through Thetford Mines to the Vermont border, and in Vermont it is represented by isolated lenses of talc and serpentine. Most of this field trip guide is for the vicinity of Thetford Mines, but two stops are for the vicinity of Asbestos, nearly half way south in the 100 miles to the Vermont border (Fig. 1).

TECTONIC EVOLUTION

THE SCIENTIFIC INQUIRY

The Thetford Mines rocks are altered, but the structures and textures are preserved. The large asbestos mines of the region are developed in serpentinized ultramafic rocks of the ophiolite. It is now commonly believed that the ophiolite was emplaced by obduction on the continental crust in Ordovician time, during the closing of the proto-Atlantic Ocean. Though the slab is deformed, it is not severly dismembered, and the selected outcrops of this field guide provide an opportunity to examine rocks of an ancient ocean crust and sedimentary cover.

This opportunity was scarcely dreamed of in the mid-1950's, when the Mohole Project was designed. The goal had been to obtain samples of the ocean crust and upper mantle by drilling a deep hole, perhaps near Hawaii. When Congress ended the funding in 1966, because of the needs of the space program and the Vietnam involvement, geologic interest had already waned. The reason was that in the early 1960's, data on topography and magnetic anomalies of the ocean floor was provoking a new synthesis, which we now know as the "plate tectonics model". Instead of the permanence of ocean basins and continents, we envision the opening and closing of the proto-Atlantic (Iapetus) Ocean in the Paleozoic, and the fragmentation of Pangea starting about at the end of the Triassic. In the process, parts of ocean lithosphere plates have been raised above sea level, to form outcrops such as the famous Troodos massif of Cyprus and the Semail complex of Oman. Bailey and others (1975) summarized the ophiolite project of the International Geologic Correlation Program. They did not mention Thetford Mines, perhaps because our understanding of this area had scarcely received wide attention.

The year 1975 was a milestone in the scientific inquiry that is directed toward deciphering the tectonic evolution of the Quebec Appalachians. Until about 1972, the main efforts had been to delimit and identify the major tectonic units of the region. Much of the work was done by St. Julien of Université Laval in Quebec City. He had spent more than a decade in detailed and regional study of the stratigraphy and structure. Incidentally, he answered a question that had puzzled Cooke (1937, p. 18), who had mapped the area around Thetford Mines and who had noted that the sandstone beds of the Caldwell Group are coarsest at the top. St. Julien (St. Julien and others, 1972, Stop D-3) used these graded beds to show that an entire broad belt of Cambrian sediments is upside down. Lamarche (1972) studied the Thetford Mines complex, but his interpretation of its origin did not answer some regional questions.

Two related developments in geoscience now began to shed light on the evolution of the region. One, of course, was the formalized model of plate tectonics (Morgan, 1968; Isacks and others, 1968). The other was the growing awareness that many ophiolites could represent ancient ocean basement (Conference Participants, 1972). In 1972, Yves Hébert, working under Laurent at Université Laval, began to study the East Lake sequence near Thetford Mines. The ocean-floor sediments on top of the ultramafic and mafic rocks "put the icing on the cake" -- the Thetford Mines complex is a complete ophiolite that evidently represents a "flake" of ancient ocean lithosphere (Laurent, 1973b) and so is an important part of the Quebec Appalachians. The ophiolite occurs within the Internal Domain (Inner Zone), which here is the lower part of an enormous recumbent fold overturned to the southeast. To the northwest, the smaller nappes and thrust sheets make up the External Domain of the Quebec Appalachians (St. Julien and Hubert, 1975; Outer Zone of Laurent, 1975a).

THE OBDUCTED SLAB

In the vicinity of Thetford Mines, the obducted slab, or "flake", is nearly intact; it is 6 or 7 km thick and consists of two units. The lower unit is composed of tectonized and serpentinized dunite and olivine-rich peridotite. The peridotite is tectonically detached from its original position in the oceanic lithosphere along a basal sole of serpentinite and, locally, amphibolite. The upper unit (Fig. 4) has a highly sheared basal zone of dunite; above this is a layered sequence of serpentinized dunite and pyroxenite, gabbro, lower massive and pillow basalts, and argillites. Depositionally above the upper unit is the younger volcanic sequence of pillow lavas and volcanic breccias (more andesitic than the lower group), and argillites and ribbon cherts (Fig. 4). The upper unit is less than 1.5 km thick at East Lake. The boundary between the lower and upper units is a tectonic shear zone; no transition zone has been found.

The lower unit is interpreted as ancient upper mantle, and the upper unit as ocean crust with sediments and a younger volcanic sequence (island arc assemblage?) (Laurent, 1975a). An alternative interpretation is that the entire slab represents only ocean crust and its cover, which sheared off at the base of or within the lower-velocity serpentinized ultramafics (Clague and Straley, 1977). In either case, the lower unit would represent rock plastically deformed at the spreading ridge, and the upper unit would be rock that has not been deformed (except at its base). Geochemically, the ophiolite resembles boninites of the Mariana Trench and so would represent a fragment of oceanic lithosphere formed in the fore-arc of a subducted zone; this fits the Sm-Nd data of Shaw and Wasserburg (1984).

Smaller masses of peridotite are interpreted as pieces of ocean basement that were tectonically detached from the basal peridotite sole of a complete ophiolite and were sliced into the country rock. The Pennnington Sheet, an extensive ultramafic sheet of dismembered ophiolite (Fig. 2), is a conspicuous example, and the many small ultramafic fragments, such as the lenses that extend south through Vermont, may have a similar origin.

SYNTHESIS

The outline of the tectonic evolution, as presented here, is based mostly on Laurent (1975a,b) and Laurent and Hébert (1975, 1977). In Cambrian(?) time, the assemblage of ultramafic and mafic rocks was formed at the spreading ridge of the proto-Atlantic. As the plate moved away from the ridge, red cherty argillite, at least 60 m thick, accumulated on the ocean floor. Perhaps as a separate and later event, a younger ocean-floor sequence was deposited on this: basaltic and andesitic lava, pyroclastic agglomerate, siliceous tuff, and sedimentary breccia, mudstone, and chert. Meanwhile, the Rosaire Formation and Caldwell Group accumulated as muds and sands on the continental rise of the tectonically quiet trailing edge of the ancient North American continent.

In Early Ordovician time, the proto-Atlantic Ocean was closing. The subducting plate was probably dipping southeast (Laurent, 1975a). At this time, the Thetford Mines ophiolite was probably detached from oceanic lithosphere. Early in the Middle Ordovician, subduction began to involve the continental margin. A "flake" of the ocean lithosphere moved relatively northwest onto the continental crust, deforming and inverting the continental rise sediments. The St. Daniel Formation was formed as a black mud with abundant and varied clasts. The breccia has blocks (to 20 m) of Cambrian metasediments, and in the belt that extends through Coleraine (Fig. 5), there are also fragments of ophiolite in the breccia. Just before Black River time (about 450 million years ago) in the Middle Ordovician, flysch began prograding northwestward across the older rocks, to form the Beauceville and St. Victor formations of the Magog Group. The source of the flysch was to the southeast in the arc assemblage (Ascot-Weedon metavolcanics) associated with the subduction zone. To the northwest, continental rise sediments and shelf sediments began telescoping toward the northwest, forming the series of nappes and imbricate thrusts of the Outer Zone.

This synthesis, which has emerged largely from the efforts of geologists in Quebec City, gives a framework for continuing research into the regional evolution and into the petrologic character of the upper part of oceanic lithosphere. Vermont's interest is obvious; understanding the Quebec geology gives a firm basis for our inquiry into the origin of the ultramafic belt that extends south through the middle of our state.

FIELD TRIP GUIDE

The field trip guide includes stops at 17 localities, most of which are shown in Figure 2. Stops 1 to 5 are in the vicinity of Coleraine and give examples from the base to the top of the obducted slab, including both the lower and upper units and the younger volcanic sequence. Stops 6 and 7, south of Mont Adstock, show sheeted intrusives in the gabbro and a magnificent roadside display of pillow basalts. Stop 8 is at an abandoned talc pit in the Penningtonite Dike, northeast of Thetford Mines; stops 9 to 11, which are east of Thetford Mines, show types of deformation in the Caldwell Group. Stop 12 near Mont Adstock, is a roadside example of the breccia (melange?) in the St. Daniel Formation.

Five stops can be visited on the way south toward Vermont. Stop 13 looks at the amphibolite sole of the lower unit. Stops 14 and 15, northwest of Garthby, are at good roadside displays of pillow lava and sheeted intrusives. Stops 16 and 17 are near Asbestos, and they show the continuation of Thetford Mines geology toward Vermont. Chemical data for local rocks are appended.

This field trip guide is designed to be used without a "leader" who is familiar with the area. Each group using the guide should determine its own sequence and choice of stops. As an aid to planning, most of the road logs in the Thetford Mines area start at Route 112, which extends northeast through the area (Fig. 2). Figures 5, 9, and 11 show surfaced roads (solid lines) and gravel roads (dashed lines). These maps were prepared from published topographic maps and the roads have not all been field-checked; therefore it is wisest to stay on the surfaced roads where appropriate. The geology on these figures was compiled mostly from Hébert (1979). Contacts and symbols are explained in Figure 2. Plan on an average speed of 40 mph on Route 112 and 30 mph on other roads. Estimated time away from vehicles is given for each stop. Additional data in the title of stops, such as E-6, SJ15, means the locality is also described in St. Julien and others (1972, Stop E-6) and/or in St. Julien (1980, Stop 15).

There are campgrounds and motels in the Thetford Mines area; phone the Thetford Mines Chamber of Commerce (418+335-3441) for a list. A number of people in the area are fluent in English, but it is helpful if at least one member of the group is comfortable speaking French, the official language.

ACKNOWLEDGMENTS

The field trip guide is revised and expanded from Baldwin's 1976 mimeographed version. Pierre St. Julien, Yves Hebert, and David Clague offered useful suggestions for the original version. For the present version, Doolan added stops for the Asbestos and Richmond areas. Further revisions were made during the August 1984 VGS field trip; participants included Jeanne Detenbeck, Ballard and Sandria Ebbett, Jeffrey Pelton, and Hugh Rose. Laurent provided additional material in October 1984. Special thanks are due to J. Detenbeck, VGS Editor.

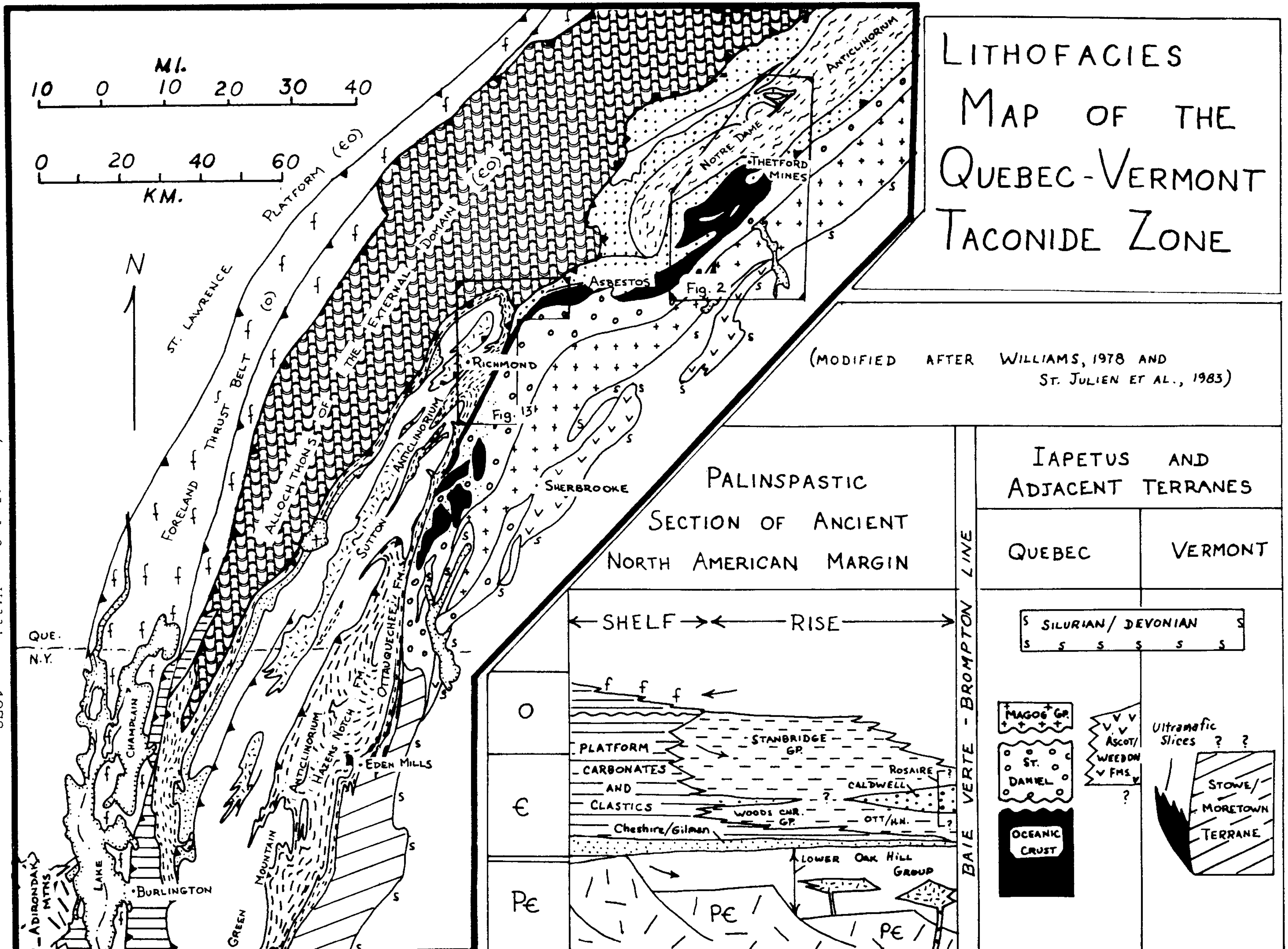


Figure 1. Regional setting (compiled from Williams, 1978 and St. Julien and others, 1983).

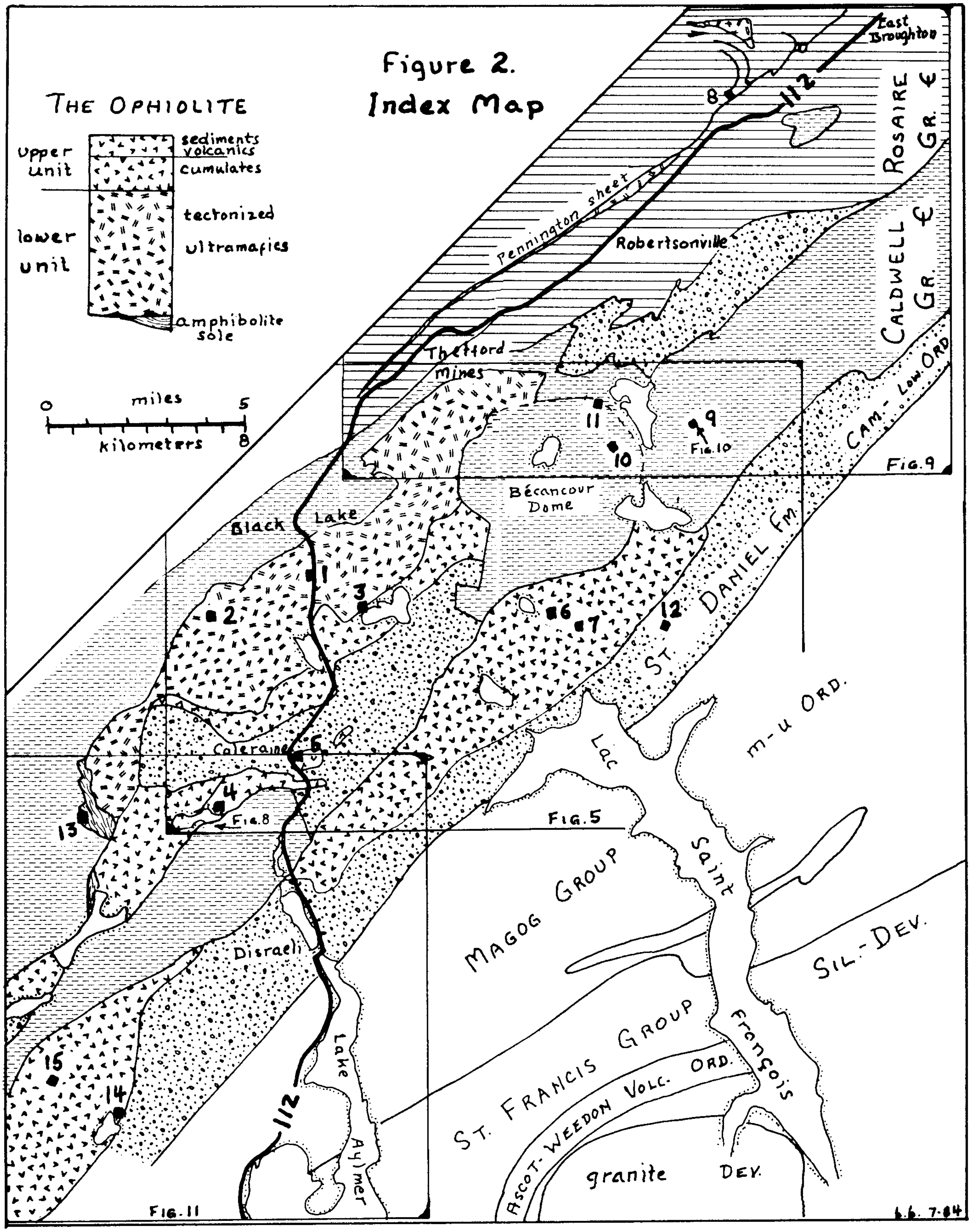


Figure 2. Index map, mostly from Yves Hébert (1979).

ROAD LOGS

Stops 1 to 5, near Coleraine

These stops give examples from the base to the top of the obducted slab; they are in the Black Lake ophiolitic massif of the Thetford Mines complex (St. Julien, 1980). Roads are shown in Figure 5.

Stop 1. Lower Unit at Black Lake 20 minutes E-5

On Route 112, 6.6 miles south of Thetford Mines, or 4.6 miles north of Coleraine. Park on shoulder of Route 112, headed south, by the deep open pit mine (Lake Asbestos Mine).

The rocks are in the lower unit of the obducted slab. The contact with the underlying Cambrian metasediments is a shear zone that occurs on the north side of the mine. The rock is mostly harzburgite, an olivine-orthopyroxene rock (Fig. 6). On the far side of the open-pit mine there are light-colored tectonic inclusions and pods of foliated and partly rodingitized granodiorite and granite. These rootless rocks occur only in the lower unit; they were faulted into place after partial serpentinization of the lower unit (Laurent and others, 1984). The accompanying deformation of the granite was at low pressure and less than 500°C; K-Ar ages indicate the granites cooled about 450 m.y.a. and this age in turn is the probable age of formation of asbestos veins.

Outcrops east of the highway show tectonite fabric, a later spaced "cleavage", and cross-cutting asbestos veins. These features are well displayed at Stop 2.

The pit was opened in 1958, after most of Black Lake had been drained and the Bécancour River had been diverted. In past years, "crude asbestos" with fibers longer than 3/8 inch were hand-picked before the bulk of the ore was milled for the shorter fibers. However, 99 percent of the asbestos in this district is short fiber, and all the ore is now milled.

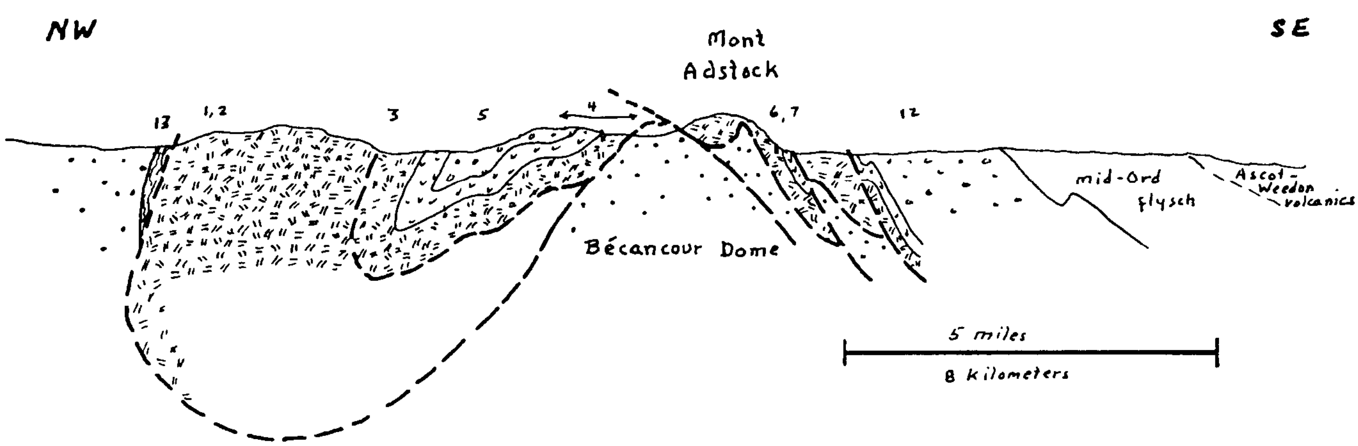


Figure 3. Diagrammatic cross-section, showing stops (modified from Laurent, 1975a).

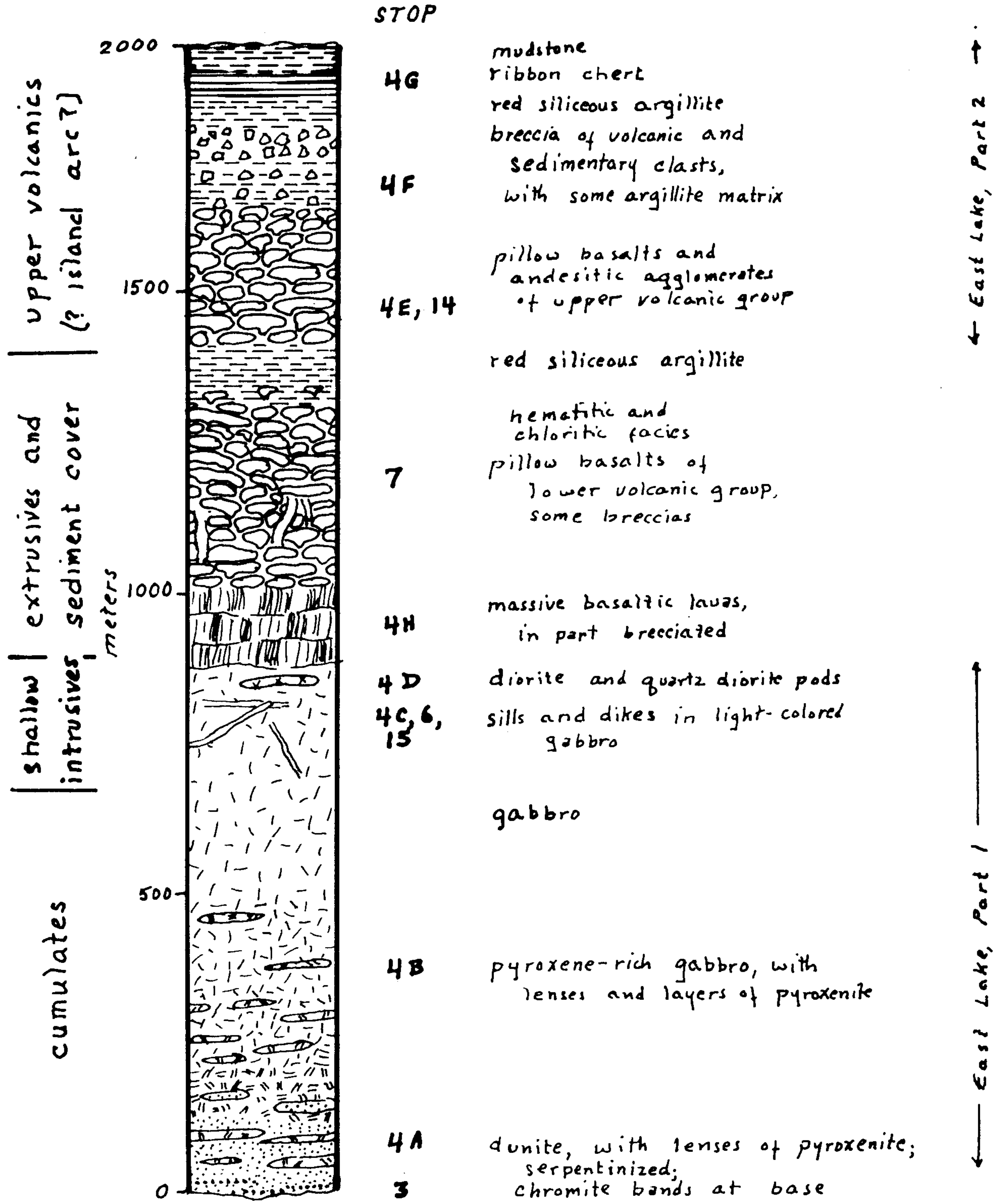


Figure 4. Upper unit and upper volcanics (after Laurent and Hébert, 1977).

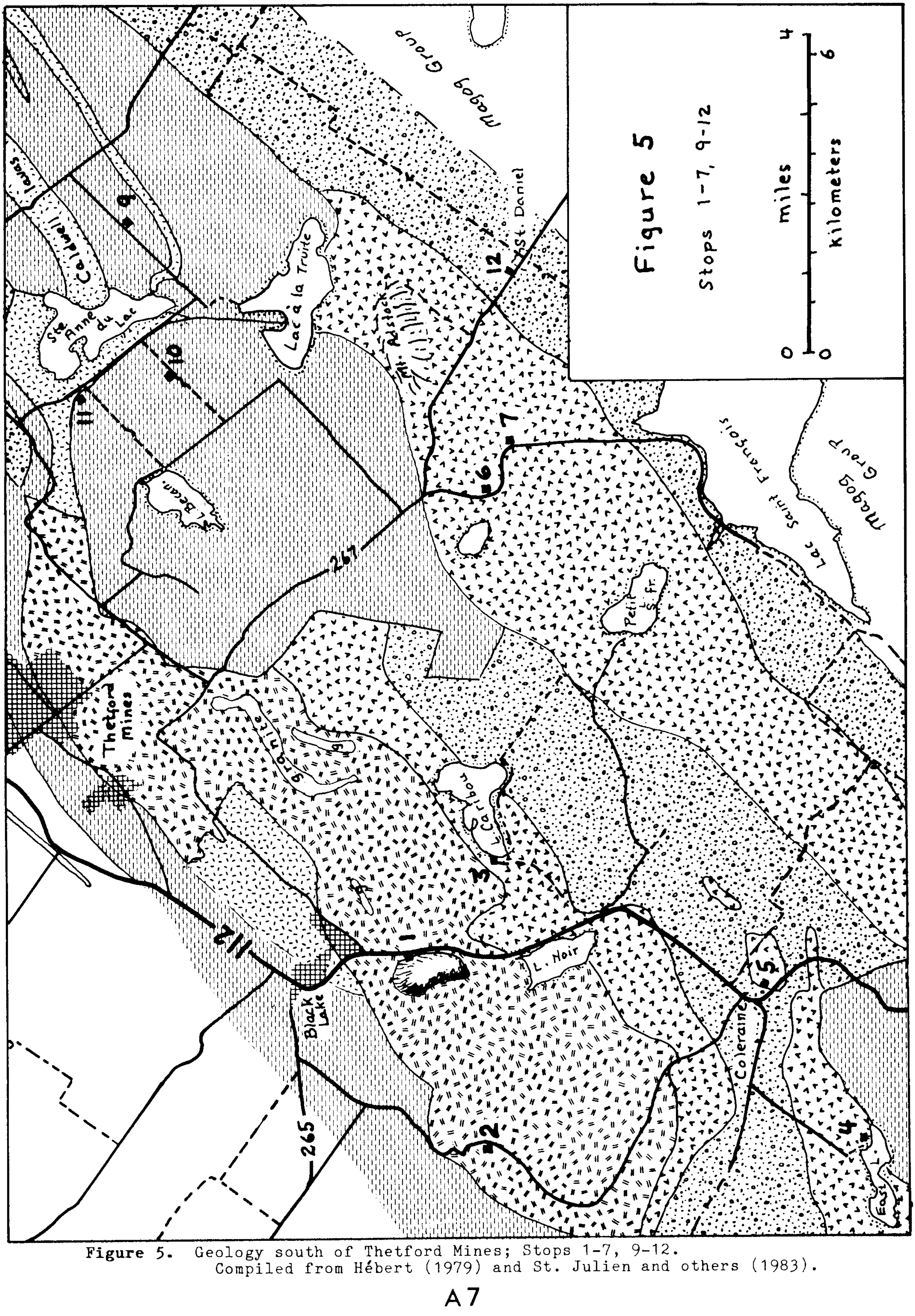


Figure 5. Geology south of Thetford Mines; Stops 1-7, 9-12. Compiled from Hébert (1979) and St. Julien and others (1983).

Stop 2. Lower Unit at Vimy Ridge Mine 1 hour E-2, SJ13

0.0 Junction of Route 112 and 265; go west on 265.

1.0 Turn left off 265.

2.0 Road to west.

2.2 Bécancour River

2.7 To east, the north end of Lake Asbestos mine.

3.0 Conveyor belt overhead! Road rises on long hill.

3.9 Curve to left.

4.1 Slow; park across from red hydrant, by the highest of three houses.

(Alternate route to Stop 2: near north part of Coleraine, turn west toward community of Vimy Ridge; the turn-off is by a grocery store and hotel. At 4.9 miles, just beyond hilltop, slow and park at red hydrant on right, opposite highest of three houses.)

Cross road to the highest house and walk on the right (downhill) side of the house. Get on a level path that bears right; within 100 m, bear right at the head of an abandoned open pit mine (Vimy Ridge Mine), and go onto the weathered outcrop.

Two kinds of ultramafic rock occur here; see Figure 6 for terminology of ultramafic rocks. The brownish-orange rock is harzburgite, which averages 85% olivine (Fo_{90}), 14% orthopyroxene (En_{93}), and chrome spinel. The rock has a porphyroclastic texture. The bold-weathering orthopyroxenes form porphyroclasts 1 to 30 mm long. The forsteritic olivine grains, 0.5 to 5 mm in size, form a microblastic matrix and are partially altered to lizardite (a serpentine). Chrome spinels form tiny black specks, commonly as linear groups of several specks. The harzburgite is cut by veins of chrysotile asbestos, which are bordered by pure serpentine (Fig. 7). The second ultramafic rock is a chromite-bearing dunite, exposed in the east part of the outcrop. The dunite weathers yellowish orange and it is smooth weathering, due to the absence of orthopyroxene porphyroclasts and asbestos veins. The dunite lenses are about parallel to the foliation.

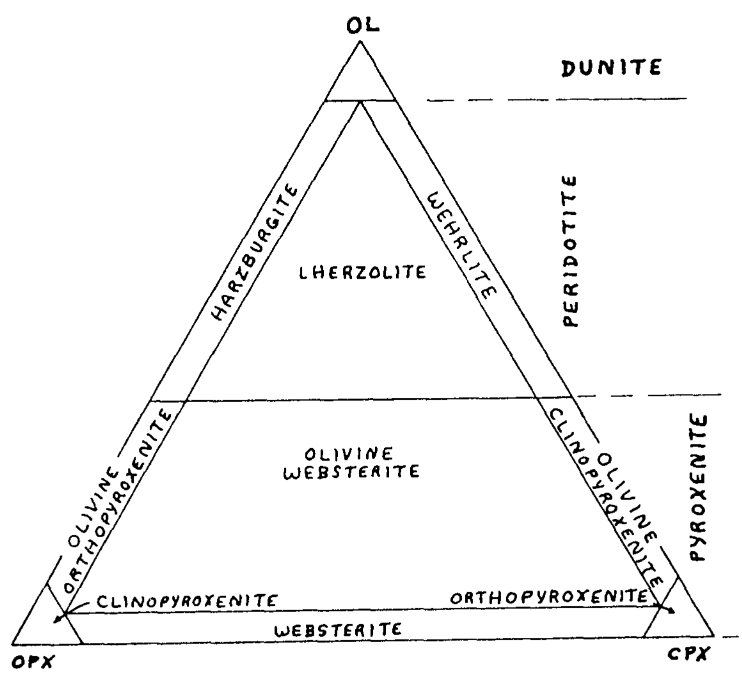


Figure 6. Terminology of ultramafic rocks (after Streckeisen, 1974).

In general, the lower unit is a homogeneous harzburgite. In some places near the base, such as at this locality, dunite pods occur. Still higher in the lower unit, as on Mont Caribou (the mountain to the southeast), there is abundant mineralogic layering in the peridotite and the layers are isoclinally folded. The lower unit is cut by dikes of orthopyroxenite and gabbro, and (as noted at Stop 1) contains fault slices of granitic rock. A traverse down into the pit and across to the re-entrant on the far side permits sampling of a 0.5 m quartz monzonite sheet-like body that has talc-chlorite rims.

The outcrop shows several fabrics. Two are somehow aspects of the primary foliation; they include: 1) lines of tiny black spinel grains that strike N 20 W and dip steeply SW, and 2) elongation of orthopyroxene porphyroblasts at a high angle to the spinel lines. A different fabric is clearly later because it shows as a "spaced" cleavage that strikes ENE and dips N at a moderate angle. Both fabrics predate the asbestos veins, and post-vein faults trend N 35 E.

The two aspects of primary foliation evidently developed as a tectonite fabric at high temperature through solid flow during formation of the ocean lithosphere. The spaced cleavage is a cataclastic deformation that probably occurred when the ophiolite was detached from the lithosphere, in the early stages of obduction.

There are at least two times of serpentinization. The first is a pervasive but partial (about 40 percent) alteration in which olivine is partly altered to lizardite, and pyroxene may alter to bastite (a serpentine pseudomorph of pyroxene). This serpentinization is younger than the blastomylonitic fabric. The chrysotile veins, which may also contain some brucite and magnetite, indicate the second serpentinization. The veins reflect brittle fracturing of the harzburgite, under conditions where the dunite was not brittle. Indeed, in this district, the asbestos is restricted to the harzburgite of the lower unit. Moreover, it occurs in the northwest part of the Thetford Mines complex, near the contact with the Caldwell Group (St. Julien, 1980, p. 70).

The first serpentinization, at a temperature below 340°C (Cogulu and Laurent, 1984) was incomplete but pervasive and it post-dates the tectonite fabric. This serpentinization of the harzburgite would have occurred during formation of the lithosphere, as upper mantle rock. Clague and Straley (1977) would infer that the serpentinization and cooling transformed the hartzburgite to crustal rock. In any event, while most of the lithosphere plate was being subducted, the weaker and more mobile serpentinized part sheared off to become the lower unit of the obducted slab, and the upper unit in turn was sheared somewhat from the lower unit. The asbestos veins are scarcely deformed and so must have been generated by meteoric waters during and after the time the slab was emplaced on continental crust (Cogulu and Laurent, 1984).

Continue east on road 4.9 miles to Route 112 at Coleraine.

Figure 7. Veins of crysotile asbestos in harzburgite at Stop 2.

Stop 3. Base of Upper Unit at Lake Caribou 1 hour

0.0 Side road on east side of Route 112. The turnoff is 2.2 miles south of Stop 1; it is about 2.4 miles north of Coleraine and 1.0 miles north of a railroad crossing. Cross railroad tracks on side road; just across tracks turn sharp right, next to tracks.

0.8 Turn left and go northeast up hill.

3.0 Turn left onto dirt road, heading northwest.

4.6 Continue straight, past road on right. At shore of Lake Caribou, turn sharp left.

4.8 Turn sharp right, along lake shore.

5.8 Park near entrance to private drive on left. Walk in, **ask permission to walk across small bridge.**

Walk around west end of lake, on tailings outwash, and turn right on the north side of the lake. About 100 m in, walk up the mine dump to the west and along a little creek to the abandoned open-pit mine. The walk takes 10 minutes.

The rocks are dunite and chromitite, which occur at the base of the upper unit. The true thickness of this interval has not been determined because the rock is tightly and isoclinally folded. However, the interval forms a belt several hundred meters wide and has been traced along the southeast face of the adjacent ridge for 2.5 km.

The chromitite occurs in the center of the pit. It forms four or five layers, 10 to 60 cm thick, which are interbedded in a thick interval of chromite-bearing dunite. The cumulate (crystal-settling) origin of these rocks is well illustrated by graded bedding in the chromite-rich layers and by alternation of these with chromite-poor layers. Here, the layering strikes N 50 E and dips about 75 NW. Chrysotile veins, which are so common in the harzburgite of the lower unit, are uncommon here. Tectonic deformation of the basal cumulates is seen in the pull-apart texture of the thin chromite horizons. Also, the dunite matrix is recrystallized and serpentinized.

In the past, prospecting for chromite showed the occurrences to lie in a band, but there was no understanding of the genetic relations (Cooke, 1937). It is now known (Thayer, 1964) that chromite deposits of possible economic value are typically located in the deformed cumulate dunite deposits. The higher grade deposits here are in concordant to sub-concordant sheets and lenses, and even strings. Chromite tends to be higher grade where the deposits are most attenuated, being 15 to 50 percent ore (Cr_2O_3) in sheets, up to 90 percent on the limbs of flowage folds, and 100 percent ore in boudins along the crests of folds. Evidently, most of the near-surface high-grade ores have been mined, but much disseminated (10 percent ore) remains.

Return to car; return to Route 112.

Stop 4. The Upper Unit at East Lake 3 to 5 hours

0.0 Coleraine. Drive south next to railroad tracks until tracks turn.

0.3 Turn right and cross railroad tracks, on road west toward St. Julien.

1.1 Slow for turn; county line; enter Compté Wolfe from Compté Megantic.

1.3 Sharp left turn toward Lac de l'Est, before crest of hill.

2.7 Sharp left onto side road into Lac de l'Est.

3.4 Park at east end of East Lake (see Fig. 8). Sandstone of the Caldwell Group crops out to the southeast, at the edge of the woods.

This stop is the most important one in the field trip guide, because it provides a nearly complete traverse of the different layers that make up the upper unit (Laurent and Hébert, 1975, 1977). The layers dip steeply and they strike northeast, with the top toward the northwest (Fig. 8). The stop is in three parts. Part 1 examines the layered ultramafic sequence of dunite and peridotite, and the mafic sequence of gabbro and the quartz-rich differentiates. It can take 1.5 to 3 hours, depending on route (see below) and ends at the main road. Drivers can walk back along the side road and bring vehicles to the parking area at the main road. Part 2, which takes 1.5 hours, examines the ocean-floor sediments and upper volcanics. Part 3, taking one-half hour including driving time, examines massive basalts on the north side of the lake. Figure 4 summarizes the sequences of layers in the upper unit, and Figure 8 shows localities A to H.

The ultramafic rocks of the lower and upper units differ petrologically, in that the pyroxene of the upper unit is clinopyroxene (diopside) whereas the most common pyroxene of the lower unit is orthopyroxene (enstatite). Another difference is conspicuous in outcrop. The ultramafic rocks of the upper unit have a cumulate (crystal-settling) origin, as shown by the crude layering, whereas in the lower unit, deformation developed a tectonite fabric that obscures any cumulate fabric.

Elsewhere (for example Stop 3 at Lake Caribou), the base of the upper unit is a well-layered dunite with chromite-rich bands that demonstrate the cumulate origin. Here at East Lake, the chromitite interval is missing, and the base of the upper unit is a tectonically sheared serpentinite. There is a covered interval on the south side of the lake, about 100 m wide, separating the upper unit from the underlying Caldwell Group sandstones.

Part 1. Look for three deformations in the Caldwell sandstone, which crops out at east end of the lake. Walk back up road to base of hill and take logging trail to east. There are two possible routes.

The faster route (1.5 hours) starts at A'-B'. Go about 20 m along the logging road and then up the hill. This traverse parallels and stays within view of the road. On this traverse, the first rocks are serpentinites and pyroxenites, but bold outcrops show the change NW into gabbro. Once in the gabbro, work back down to the road, walk NW along the road; go to NW end of hill at C, thence to D. (See below for rock descriptions.

The longer route (3 hours) starts at A. Go along the logging trail for about 210 m, then into the woods on left (NW) to the base of a hill (A in Figure 8). Look for orange tape that flags the trail. The route from here is up the outcrops of this low hill and obliquely west, to a bare hilltop (B) that gives a view west along the lake. From here, the trail goes northwest (parallel with the side road) across a series of knobs. The northwest knob (C) overlooks open fields (D) and the main road.

[Stop 4 continued on Page 13]

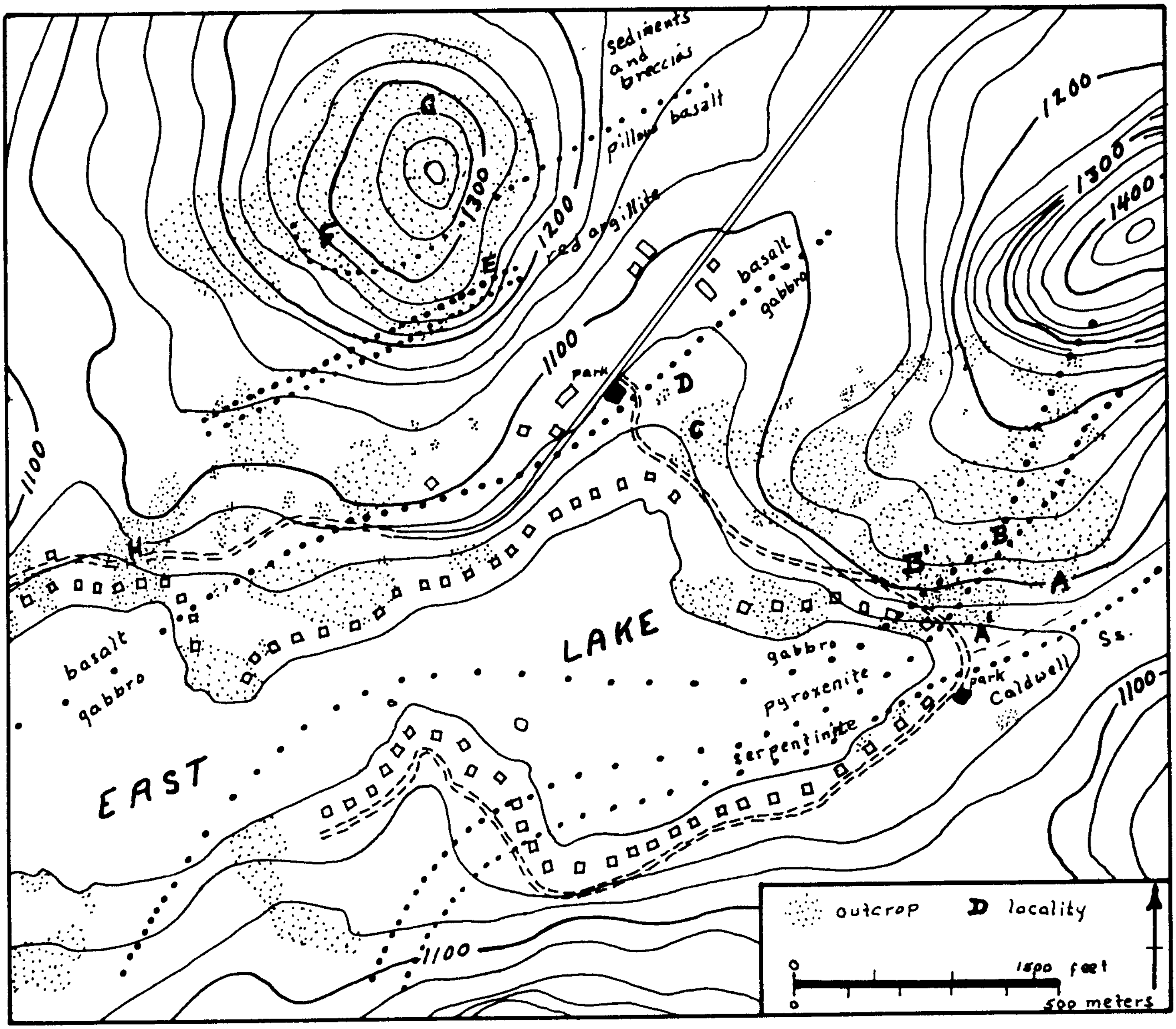


Figure 8. The upper unit at East Lake; Stop 4 (compiled from maps of Hébert).

From the base of the hill (A) to the lookout on the hilltop (B), the rocks change upsection from schistose to massive serpentinite, then to mostly pyroxenite (websterite; see Fig. 6) with some crude layers of serpentinized dunite and wehrlite. In these rocks, pyroxene is uralitized to fibrous amphiboles and olivine is serpentinized. The serpentinization diminishes up the hill, though some brown-weathering serpentinized wehrlites can be seen on the hilltop.

The traverse upsection from the hilltop (B) is not marked but goes generally northwest through the woods from one rocky knob to the next, toward (C). Occasional compass bearings are helpful. Along the traverse, there are some mylonitized pyroxenites, with 1 cm pyroxene porphyroclasts in a finer grained matrix. In addition, plagioclase (An_{60}), which is saussuritized, makes its appearance and becomes increasingly abundant as the rock layers become gabbroic. Farther on, quartz veins appear, and occasional areas of medium- to fine-grained uralitized gabbro (plagioclase An_{40}) are brecciated by sills. The last knob (C) before leaving the wooded area shows sheets of diabase and keratophyre (albitized andesite) cutting the gabbro. In the open fields (D) near the main road and parking area, there are some quartz diorites and plagioclase granites.

Generally speaking, the Thetford Mines ophiolite lacks a "sheeted dike complex" between the gabbro and basalt layers. Instead, there is a swarm of sills (a "sheeted sill complex") at some localities. Besides the swarm at Stop 6, it is seen at Stop 15, northwest of Garthby; another place is on top of Mt. Ham, southwest of the Thetford Mines area; and still another is on top of Mt. Orford, near the Vermont border. The Ligurian ophiolites of northern Italy also have a sheeted sill complex that has been interpreted as indicating a rapidly spreading mid-ocean ridge.

Part 2. Walk up the pasture slope to the edge of the woods. A faint trail starts at the huge erratic (E) at the edge of the woods and goes up a steep ledge and then obliquely left. Above the first ledge, note remains of a shack. From here, walk left, clockwise around the hill at the same elevation. On the southwest side of the hill go up onto the top of the next ledge (F). Continue northeast onto the hilltop (G).

This hill exposes the upper volcanic sequence. Near the edge of the woods (E), there are spilitized tholeiitic pillow lavas of red hematitic or green chloritic facies and a red shale matrix. Above the covered interval, there is volcanic breccia, overlain by a red breccia with shaly matrix and volcanic fragments, 2 cm beds of red chert, and red argillite (F to G). On the north part of the hilltop (G), there are red and some greenish gray ribbon cherts and mudstones. This sequence is typical of ocean-floor sediments.

Retrace route to parking area.

Part 3. If time permits, drive 0.5 miles west on the main road, on the north side of Lac de l'Est, to observe the basalt interval above the gabbro. Park and examine ledges on the north side of the road (H).

Most of this outcrop is massive metabasalt, though ghosts of pillows can be seen in some outcrops. The schistose metabasalt marks a fault separating the gabbro from the basalt. However, the transition zone between the plutonic and volcanic rocks is preserved at Mt. Ham, southwest of the Thetford Mines area.

Return to Coleraine.

Stop 5. Coleraine Breccia at Coleraine 30 minutes E-6, SJ15

0.0 Coleraine, at Hotel de Ville

0.1 Drive up hill on Messel Avenue to east side of cemetery. Turn in and park.

The glaciated knob is the most conspicuous outcrop and the unweathered lower part is still polished **(no hammers, please!)**. Also, there are polished pavement outcrops just east of the cemetery road.

> "The breccia consists of fragments of red and green and more or less silicified mudstones that must have been unconsolidated when deposited; blocks of feldspathic sandstones and of schistose sandstones very similar to those of the Caldwell Group in the Grand Morne and Becancour Dome; and some blocks derived from the ophiolite complex such as blocks of pyroxenite, gabbro, and mafic volcanic rocks. The fragments range from a few millimeters to several meters in diameter, and may be rounded or angular. Numerous mudstone galls interpenetrate one another and are severely deformed at contacts with harder clasts. The matrix of the breccia is composed of vari-colored, more or less silicified mudstone." (St. Julien, 1980, p. 71.)

The Coleraine Breccia is distinct from the dark gray St. Daniel Formation. It occurs near the northeast-trending axis of the main syncline in the Black Lake ophiolite massif. It appears to be an upward continuation of the East Lake sequence and so would be older than the St. Daniel Formation. It contains reworked fragments from the ophiolite suite, especially the upper unit. It also has fragments of the metamorphosed Cambrian metasediments underlying the ophiolite slab. Ultramafic and gabbroic fragments are the smallest and least abundant; volcanic fragments are generally larger; red and green argillite, which were still soft when the breccia formed, are the largest and commonest. Some clasts are breccias containing breccias. The argillite matrix may have been a "soup", and the breccia must have formed after the start of obduction, in response to sea-floor tectonic processes.

A second exposure of the Coleraine Breccia is on a ridgetop to the east. Access is from Route 112 near the Sport Center, onto Drovin Street. Drive southeast 0.4 miles and park at top of ridge. The 10 m face of the roadcut at the top of the hill has a block of Caldwell about 25 m long; the block is sandstone with a green chert bed and is cut by a sandstone dike.

Stops 6 and 7, South of Mont Adstock

These stops show sheeted intrusives in gabbro, and a magnificent display of pillow lava, features in the upper unit that were not seen in the East Lake traverse.

Stop 6. Sheeted Intrusives in Gabbro 30 minutes SJ16

0.0 Leave Stop 1 by the pit at Black Lake and drive north on Route 112.

0.7 Turn right (northeast) off Route 112, just before bridge.

3.6 Road bends right and then left.

4.5 Slow for sharp right turn; railroad underpass; continue southeast.

5.1 Intersection with Route 267. Continue straight, onto Route 267, headed southeast (right fork). This junction is at 5.1 miles on road log for Stop 12.

8.7 Continue southeast; road enters on left.

9.0 Slow for road junction; take right fork. Left fork goes to Stop 12.

10.0 On curve to left, slow down; park opposite cliff.

Walk to east side of road, and in 10 m to base of hill. Climb up to first good exposures.

The host rock is a fine-grained uralitized gabbro that is invaded by so many intrusive sheets that it is difficult to find large remnants of gabbro. The sheets are nearly vertical and cut the gabbro in many directions. Most are diabase but they range in composition from mafic to felsic, and textures range from aphanitic to medium grained. This outcrop shows that the injection of differentiated magmas is a complex phenomenon that has occurred in multiple events.

Stop 7. Pillow Basalt of Lower Volcanic Group 30 minutes E-4, SJ17

10.0 Continue on road.

10.6 Slow during sharp curve to right; park opposite broad low outcrop.

The outcrop that slopes west toward the road shows many features characteristic of pillow basalts (Seguin and Laurent, 1975). **No hammers, please!** Fresh samples can be collected across the road. The pillows are convex toward the road and sag into the adjacent pillows away from the road; therefore, they face toward the road, indicating a minor fold in a southeast-facing sequence. Some pillows show the narrow feeder neck; a few show the bulbous cylindrical shape of tubes; concentric zoning is distinct. The several diamond core holes represent sampling for petrographic and paleomagnetic studies (Seguin and Laurent, 1975). The matrix between the pillows is volcanic glass (devitrified) and in part is a breccia from adjacent pillows. There are a few dikes. The lava is of olivine tholeiitic composition, high in MgO and Cr and low in TiO_2. The composition is similar to present-day boninites from the Marianas Trench. Toward the south end of the outcrop, volcanic breccia forms a layer between these pillows and those in the fresh cut across the road. The pillow lavas of the lower volcanic group are about 200 m thick here, about half the thickness that is found at Mt. Ham, and a third the maximum thickness known for the Thetford Mines ophiolite.

Return to Thetford Mines or Black Lake. Or, continue south to Lake St. Francis and drive southwest to Route 112 at Disraeli, a total distance of 10.8 miles, mostly on gravel road.

Stops 8 to 12, East Half of Thetford Mines Area

These stops show the Pennington Sheet, deformation in the Caldwell Group, and the St. Daniel Formation. Figure 9 shows the roads east of Thetford Mines and all stops except Stop 12; Figure 5 shows all stops except Stop 8.

Stop 8. Pennington Sheet near Broughton Station   20 minutes   D-6

0.0 Route 112 headed northeast, at intersection with Route 267, which leads southeast into Thetford Mines.

5.5 Continue northeast on Route 112 through Robertsonville; Route 269 turns off to the southeast.

9.1 Enter Comté de Beauce; Route 271 enters from left.

10.2 Slow for left turn off Route 112, toward St. Pierre de Broughton. Broughton Station (Leeds) is to the right (southeast).

10.7 Park at mill, across from abandoned soapstone quarry.

Walk to edge of pit. The pit was abandoned in 1960, and the mill is now supplied by a nearby quarry. **Please do not go over to the far quarry wall; falling rock is dangerous there.**

The Rosaire Formation makes the upper half of the quarry wall. It is schistose and is altered to chloritic blackwall. It occurs in a series of synforms, separated by thrusts. The axial plane schistosity strikes N 70 W and dips about 40 S. There is also an earlier schistosity. A dark band of amphibolite occurs between the Rosaire synforms and the underlying talc. The talc is in the upper altered zone of the Pennington Dike. The "dike" is actually a dismembered sheet of the lower unit, perhaps 1 km thick, and it is bounded by thrust faults. St. Julien and others (1972, Fig. 12) presented a detailed map of the complexly folded rocks.

Return to Robertsonville for road log to Stops 9 to 12

Stop 9. Inverted Sandstones of Caldwell Group   45 minutes   D-3, SJ20

0.0 Robertsonville; turn southeast off Route 112 onto Route 269.

1.7 Cross-road; continue straight southeast.

4.3 Turn right onto road toward Ste. Anne du Lac.

5.1 Just past farm buildings, park at base of hill by gates.

Walk south across pasture to the outcrops (A in Figure 10) at the fence corner.

The Caldwell Group is a sequence of red and green shale, with turbidite interbeds of feldspathic graywacke; the source was a continental terrane. It includes some volcanic layers, as shown in Figures 5 and 9. The Caldwell is probably of Cambrian age, though no fossils have been found in it. Tectonically, the outcrops represent the lower (overturned) limb of an enormous recumbent southeast-facing fold or nappe.

The sandstones show several features of the Bouma turbidite model, and they are upside down. As originally deposited, they have a sharp basal contact; the massive interval grades up from coarse and perhaps pebbly sandstone to finer sandstone; this is overlain by a laminated interval and then a cross-laminated interval, which in turn grades up into the overlying shale.

[Stop 9 continued on Page 18.]

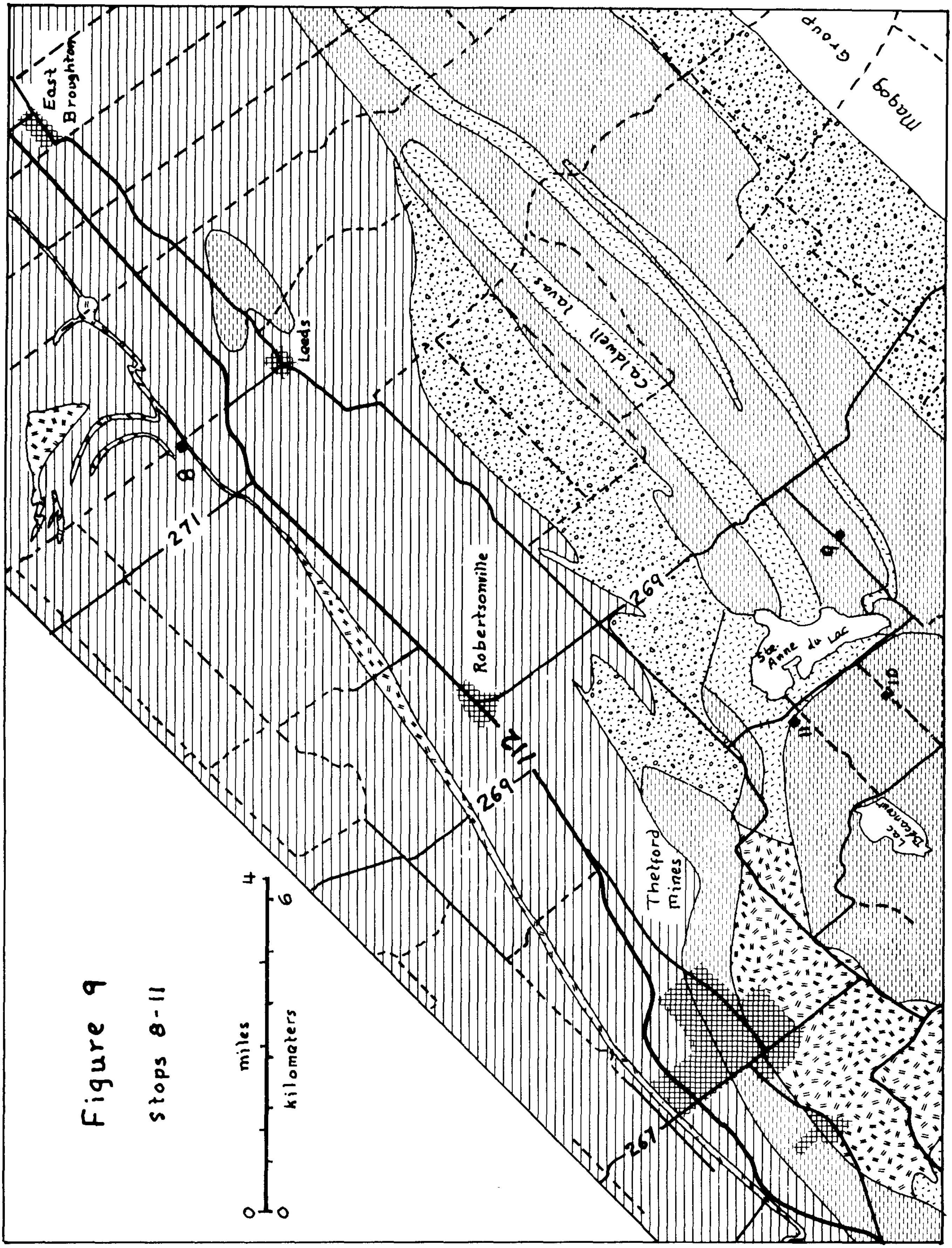


Figure 9. Geology northeast of Thetford Mines; Stops 8-11. Compiled from Hébert (1979), St. Julien and others (1972), and St. Julien and others (1983).

Follow one or two sandstone beds (with associated shales) across the outcrop to see evidence for multiple folding.

> "The rocks have undergone three phases of folding: early recumbent folds with hinges oriented northeast-southwest; open, upright folds trending north-south; and late, relatively tight folds, plunging northeast or southwest at angles of 5° to 85°, with axial planes striking N 45 E and dipping on the average 75° northwest.
>
> Schistosity is parallel to axial planes of the late folds, and the variations in the plunge of lineation result from the superposition of this northeasterly trending schistosity upon the north-south folds without axial-plane foliation. However, these two sets of folds do not explain the regional overturning of the beds in the Caldwell of the Grand Morne domain. For this reason, it is believed that the north-south and the northeasterly-trending folds are superposed upon the overturned flank of a recumbent fold that covers an area of several hundred square kilometers. Small parasitic recumbent folds can be observed on two outcrops at this stop." (St. Julien, 1980, p. 77, 79).

Return to road and cross to rock bench (B), looking north at the farm buildings. The sandstones across the little valley are upside down and are arched in an antiform. At (B), the S_3 cleavage cuts obliquely across a small early fold in the sandstone and shale on the north face of the rock knob.

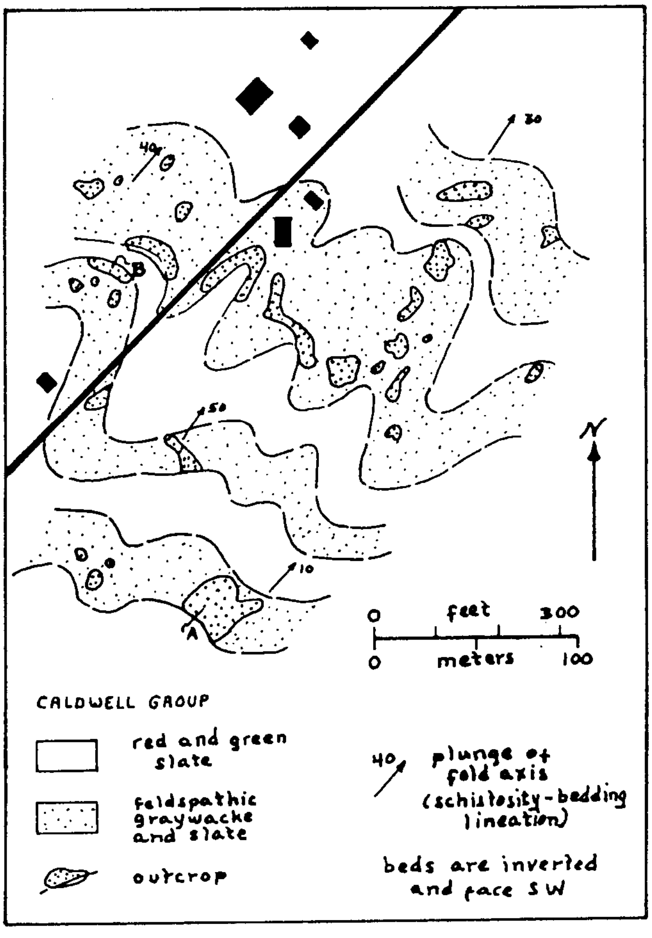


Figure 10. Inverted beds at Stop 9 (modified from St. Julien and others, 1972).

Stop 10. Metamorphosed Caldwell in Bécancour Dome 20 minutes SJ18

5.1 Continue southwest

6.5 Sharp right at southeast end of Ste. Ann du Lac (Clapham Lake); road trends northwest.

7.4 Sharp left turn onto road up hill.

7.9 Park just beyond crest.

The Caldwell outcrops along the road; from here on to the bottom of the hill are quartzites and black schists. They are considerably more metamorphosed than the Caldwell of the previous stop. Mica in the foliated quartzite has yielded a K-Ar cooling date of 441 ± 15 m.y., indicating the end of dynamothermal metamorphism was perhaps as late as late Middle Ordovician. Other dates in the region are consistent with this (St. Julien and Hubert, 1975).

In this vicinity, three sets of foliation have been recognized. The third is related to doming of the Bécancour Dome, which is the circular area in the center of Figure 2. The doming brought these metamorphic rocks up to the same level as rocks seen at the previous stop. Probably, the obducted slab was above these rocks but has been eroded in the domed area, as well as to the northeast.

Stop 11. Fault Breccia on Margin of Bécancour Dome 30 minutes SJ19

7.9 Continue southwest.

8.8 Intersection; turn right.

9.7 At Lake Bécancour, turn right onto road toward northeast.

11.1 Restaurant; slow for left turn.

11.2 Park at hilltop.

Walk across road and about 50 m into the woods onto a bare knob.

This is one of a series of knobs of fault breccia, which has been traced more than a mile along the north margin of the dome. The fragments are mostly vein quartz and Caldwell sandstone. Some "rock fragments could be put back together like the pieces of a puzzle" (St. Julien, 1980). Some sandstone fragments have quartz veins, like the Stowe Formation of Vermont. The fragments have two of the foliations, but not the third foliation, which is believed to be the result of doming. Incidentally, there is a line of small outcrops of ultramafics on the island and north shore of Ste. Anne du Lac (not shown in Figure 9), marking the north edge of the dome.

Return to vehicle. The road log below indicates the route back to Thetford Mines, as well as the route to Stop 12. An alternative route to Stop 12 is 3.2 miles shorter but on gravel roads: retrace route to Lake Bécancour, turn left, and drive southeast 1.6 miles to a sharp right turn; drive southwest another 2.1 miles to the intersection that is labeled "8.7" miles on log below.

Stop 12. St. Daniel Formation at St. Daniel 30 minutes

0.0 Leave Stop 11; continue northwest.

0.8 Intersection; turn left.

2.2 Road bends left.

3.8 Road to left goes southeast to Lake Bécancour.

4.4 Route 267 enters from right. To reach Stop 12, continue straight, onto Route 267, which comes from Thetford Mines.

5.1 Intersection. Turn left with Route 267. This junction is at 5.1 miles on the road log for Stops 6 and 7.

8.7 Road on left is where alternate route from Stop 11 enters.

9.0 Slow for road junction; take left fork with Route 267. Right fork goes to Stops 6 and 7.

10.9 Road on left goes northeast to ski area at east end of Mont Adstock; continue southeast.

12.0 Park. (St. Daniel is at the cross-roads at 12.2. miles).

The roadcut on the east side shows vertical beds of breccia and phyllite of the St. Daniel Formation. Actually, there are two sets of clast lithologies in the St. Daniel. The St. Daniel that separates the Black Lake ophiolite massif from the Mont Adstock ophiolite massif contains ophiolite fragments as well as pieces of the Caldwell and Rosaire formations.

Here, in the belt southeast of the Mont Adstock ophiolite massif, clasts include stretched sandstone and quartzite of the Caldwell and Rosaire formations; light-colored felsic volcanics(?); coarse quartz sandstone; green, gray, and black slate; and disrupted sandstone beds. North of Beauceville, P.Q., there is an enormous (10 km by 3 km) exotic block of felsic pyroclastic rocks; it is like the Chain Lakes massif, which is dated at 1.4 b.y.a. Here at St. Daniel, the matrix is black slate, in marked contrast with the Coleraine Breccia (Stop 5), which has a matrix of red and green slate. Is the St. Daniel a wildflysch -- a sedimentary breccia that was formed by Cambrian clasts slumping into black mud on the ocean floor, and later deformed? Or is it a tectonically mixed breccia (melange) that is related to a subduction zone?

The St. Daniel in this region is overlain, with probably angular unconformity, by the Beauceville, which is Black River (Middle Ordovician) in age. Published reports date the St. Daniel as Early Ordovician, but it could have formed in the 30-million-year interval of early Middle Ordovician. The St. Daniel tectonically overlies the ophilolite and it extends 300 km north from the Vermont border. It occurs on the boundary between Cambrian and Middle Ordovician formations. The Caldwell - St. Daniel boundary appears to be the Baie Verte - Brompton Line (Fig. 1), a major suture between plate boundaries, in the Inner Zone of the Quebec Appalachians.

Return to Thetford Mines.

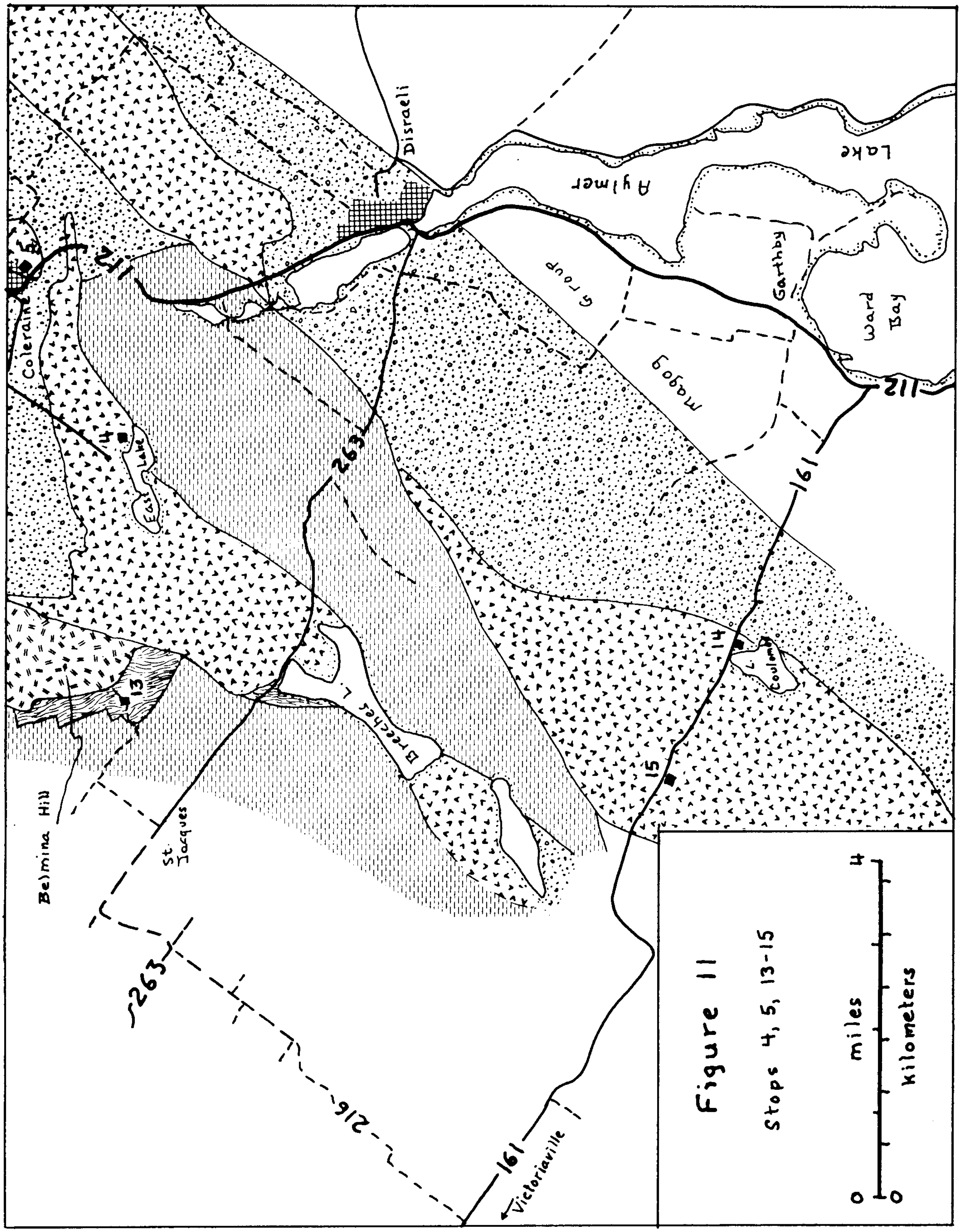


Figure 11. Geology west of Disraeli; Stops 13-15.
Compiled from Hébert (1979) and Feininger (1981).

Stops 13 to 15, Southwest of Thetford Mines

These stops show the amphibolite sole, pillow lavas of the upper volcanic group, and the sheeted sill complex; the rocks are a southwestward extension of the Black Lake ophiolite massif.

Stop 13. Amphibolite Sole 90 minutes

0.0 Disraeli, southwest end of bridge across Lake Alymer.
Turn right (northwest) off Route 112 onto Route 263.

3.6 Caldwell Formation in roadcut on right is greenish gray chloritic quartzite with some intervals of chloritic phyllite and carbonaceous phyllite. Pinstriping of chloritic laminae in coarser quartzites predates dominant cleavage.

4.7 Serpentine with relict pyroxenes in roadcut on right.

6.0 West end of Breeches Lake; long roadcut in upper unit.
Dark serpentine with lighter green felsic to intermediate intrusions.

6.3 Hilltop west of lake; schistose serpentine and then schistose Caldwell.

8.0 St. Jacques (Stenson); turn right (northeast) off Route 263.

8.9 Turn right (southeast) at T intersection;
follow gravel road narrowing southeastwards.

9.6 Park at bend in road by new house, where trail leads north.

Follow the trail going north and then northeast. The trail goes uphill across a wooded area. Walk through the amphibolite to the harzburgite; stop at an abandoned mine at the base of Belmina Hill, about 0.7 miles (1 km) and 20 minutes from the parking area. Then start the traverse back to the cars.

The mine is in homogenous harzburgite with north-trending steep foliation. On the south side of the quarry, the harzburgite becomes highly sheared serpentinite. The contact with the amphibolite sole is not seen but it trends N 30 W and is about 200 m south of the quarry.

The amphibolite occurs as a discontinuous wedge dipping steeply eastward between rocks of the Caldwell Group to the west and the basal tectonite peridotite to the east. Its maximum thickness is about 800 m along the southwest side of Belmina Hill.

The first amphibolite outcrop is about 40 m south of the inferred contact. Here the amphibolite is massive and coarse, mostly amphibolite with minor clinopyroxene, garnet, and epidote. This grades southwest into foliated amphibolite with garnet and epidote layers. Local breccias are cemented by albite, quartz, epidote, chlorite, pumpellyite and prehnite.

Two more amphibolite belts occur to the southwest. One is 150 to 500 m from the harzburgite and the other is 500 to 700 m away. These belts are locally rich in garnet (to 30 percent) and in the second belt clinopyroxene (to 20 percent). At 700 m, the amphibolite is retrogradedly metamorphosed into greenschist facies. At its tectonic brecciated contact with the Caldwell, the amphibolite is altered to dense chlorite schist.

The amphibolite could be metavolcanics of the ophiolite complex (Feininger, 1981). It has the trace-element geochemistry of mid-ocean ridge basalt (Clague and others, 1981). It contains amphibole, garnet, clinopyroxene, and epidote, with minor quartz, plagioclase, and accessory minerals. The mineral assemblages indicate temperatures from 500°C at the contact with the Caldwell to 780°C at the contact with the peridotite; pressures were 5 to 7 kilobars (Feininger, 1981).

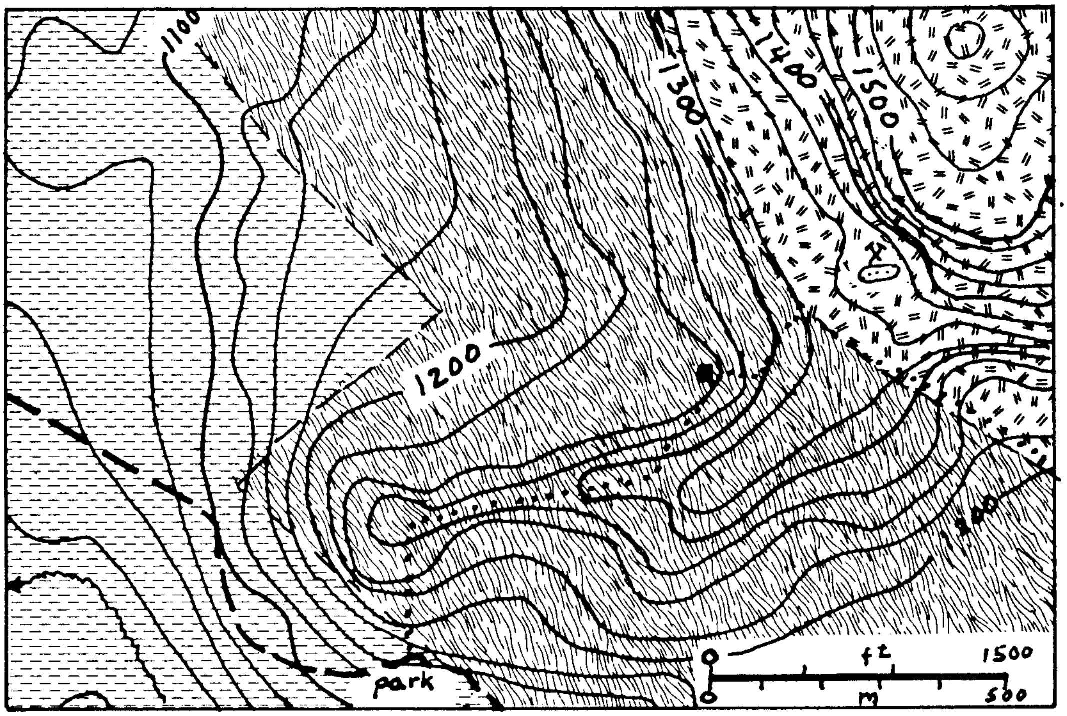


Figure 12. Amphibolite sole southwest of Belmina Hill; Stop 13 (after Feininger, 1981).

Alternate Road Log from Stop 13 to Stops 14, 15.

0.0 St. Jacques; turn right (northwest) onto Route 263.

1.2 Route 263 turns left (southwest), joined by Route 216.

2.2 Continue southwest on Route 216; Route 263 turns right.

4.1 Route 216 begins curves.

6.0 Sharp right and then left.

7.4 Turn left (southeast) onto Route 161.

11.3 St. Martyrs; Route 161 bends left.

12.0 Route 161 bends right (southeast).

13.9 Stop 15 is roadcut on right.

15.6 Lac Coulombe; Stop 14.

The following road logs for Stops 14 and 15 start from Route 112. An alternate road log from Stop 13 to Stops 14 and 15 is on page 23.

Stop 14. Pillow Lavas of the Upper Volcanic Group 30 minutes

0.0 Turn sharp right onto Route 161 (six miles southwest of Disraeli) headed northwest toward Victoriaville.

3.5 Park at head of Lake Coulombe.

Walk southeast up the hill, examining roadcuts in andesitic metabasalts and andesites. Pillows are well displayed; some tubes can be seen in the first roadcut on the southwest side. Pillows are commonly vesicular and most pillows have a thin epidote rim. Metamorphism is low grade; pumpellyite and prehnite have been identified. The layering is vertical and faces southeast. The next to last roadcut on the northeast side shows volcanic breccia above pillows, and therefore the breccia grades laterally into the pillows.

Additional exposures of tubes and pillows can be seen at the base of a series of cliffs that parallel the road and lie 100 to 200 m northeast of the road. Spilitization is localized in vertical conduits showing heavy metal sulfide mineralization. This side traverse starts at the turnout by the St. Daniel outcrop and takes about one hour.

Stop 15. Sill "Swarm" in Gabbro 30 minutes

3.5 Continue northwest.

4.3 On hill, road crosses into gabbro interval.

5.2 Slow down, 300 m after curve to left, and park across from long roadcut.

Close examination of structures and textures will reveal countless vertical sheets of fine-textured rock in a host rock of gabbro. The gabbro in places shows layering and a grading that faces southeast; the layering is nearly vertical. The hypabyssal rocks, which have chilled edges, include diabase and more sodic granitic differentiates. They cut at a low angle to the layering of the gabbro. Only a few of these sheets are visible from across the road, but use of a hammer and hand lens will show that sheets make up much of the roadcut. This sill swarm ("sheeted sill complex") and the one at Stop 6 occur in the Thetford Mines ophiolite in the position where most other ophiolites have a sheeted dike complex.

Stops 16 and 17, Asbestos and Richmond, Quebec

The Asbestos ophiolitic massif has many similarities to the Thetford Mines ophiolite complex. Although the upper unit is drastically thinned in comparison, the lower unit, complete with the amphibolite sole, is well displayed. Tours of the Jeffrey Mine are available if arrangements are made well in advance. Access to the mine provides an excellent opportunity to sample the amphibolite sole along the north rim of the pit and to observe the rootless granitic bodies intruded into the lower unit in the pit itself. In addition, an excellent transition from pyroxenite to gabbro is nicely displayed in cuts bordering the parking lot on the west side of the processing plant.

The following road log starts at Stop 15 on Route 161.

Stop 16. Burbank Hill, Asbestos, Quebec 60 minutes

0.0 Leave Stop 15. Proceed northwest on Route 161.

9.2 Bear left with Routes 161 and 216; Ham Nord straight.

11.2 Turn left with Route 216; Route 161 goes straight.

14.1 Pavement ends.

17.0 Pavement begins.

17.4 St. Adrien; continue straight; Route 257 goes southeast.

24.8 Turn right onto Route 255.

32.4 Turn left onto Route 249 (see Fig. 14).

33.7 Cross intersection; continue on Route 249.

34.8 Route 249 ends; turn right.

35.1 Take left fork.

35.3 Turn sharp left.

36.2 Park by gate to quarry road.

Walk uphill to floor of road metal quarry (Fig. 14).

The quarry consists of diabase and gabbro of the upper unit of the Asbestos ophiolite. From the quarry floor climb the south wall to the main rim. In the adjacent woods note unusual breccia. Clasts in the breccia include a variety of felsic intrusive rocks (granite, syenite, granodiorite); mafic intrusive rocks (hornblende gabbro, norite, diabase, and microgabbro); volcanic rocks (hornblende basalt, trachyte, andesite?) and a variety of chloritized ultramafic cumulate rocks. The origin of the breccia is problematical; Lamarche (1973) interpreted it as a volcanic breccia; Church (1977) treated it as a sedimentary breccia unconformably overlying the gabbro and Scholz (1981) agreed. The lack of a penetrative foliation or any deformational fabric near the contact with either unit seems to preclude a tectonic origin. Locally, amphibolite, metamorphosed volcanic rocks and quartz clasts of metamorphic origin are present (Scholz, 1981). All components of the upper unit of the ophiolite are present, (Scholz, 1981) but unlike the Coleraine Breccia there are no clasts of sedimentary rocks or of the lower unit.

Proceed down the hill toward the cars. Note that the breccia is overlain by red shales. The contact between the breccia and the red shales appears to be conformable and stands in marked contrast to the highly irregular gabbro-breccia contact. Although not exposed here, the red shales are overlain by black olistostromal shales of the St. Daniel Formation. A possible analogue of the Burbank Hill Breccia is the Crabb Brook Group which unconformably overlies gabbro, sheeted dikes and pillow lavas of the Bay of Islands ophiolite in western Newfoundland (Casey and Kidd, 1981).

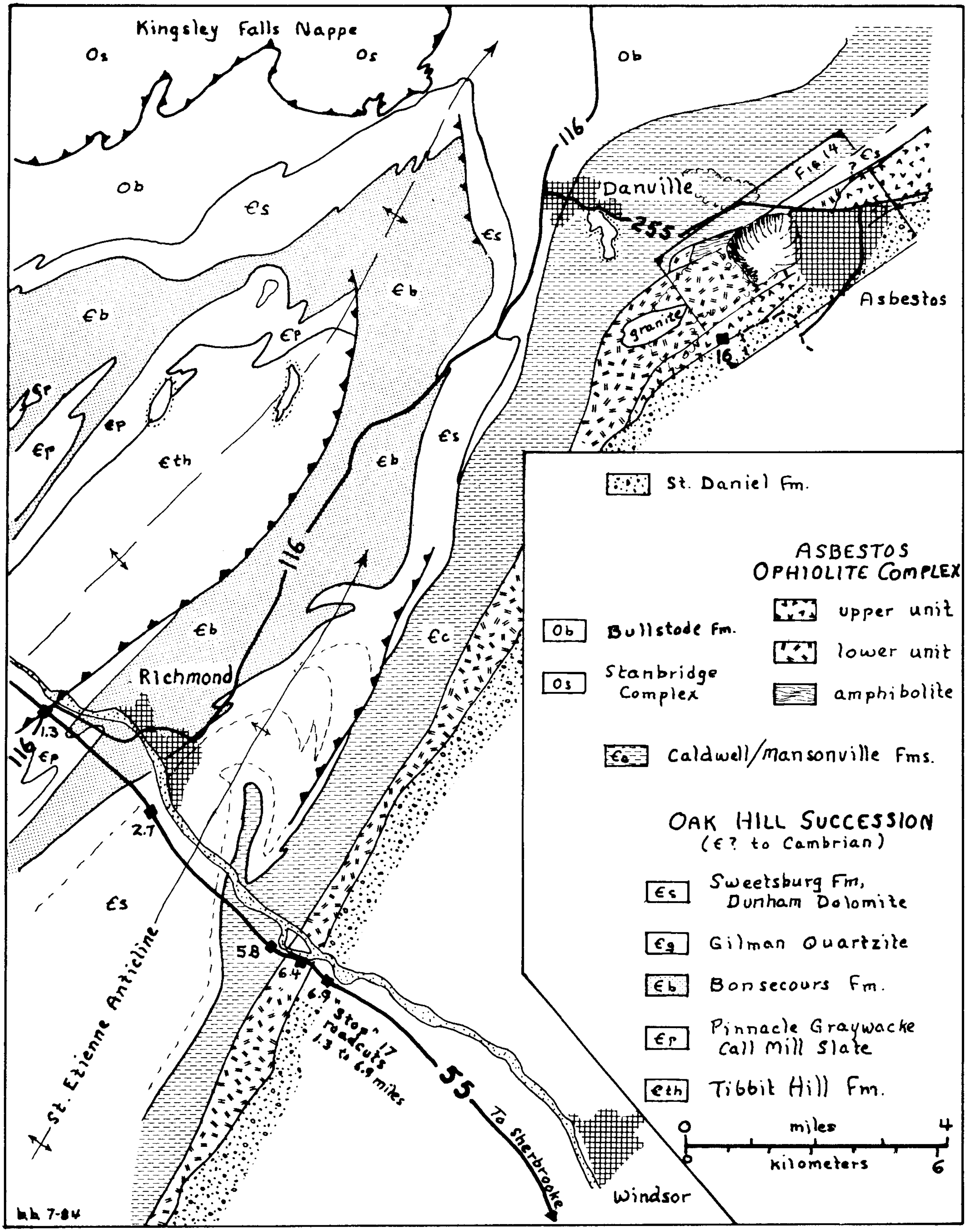
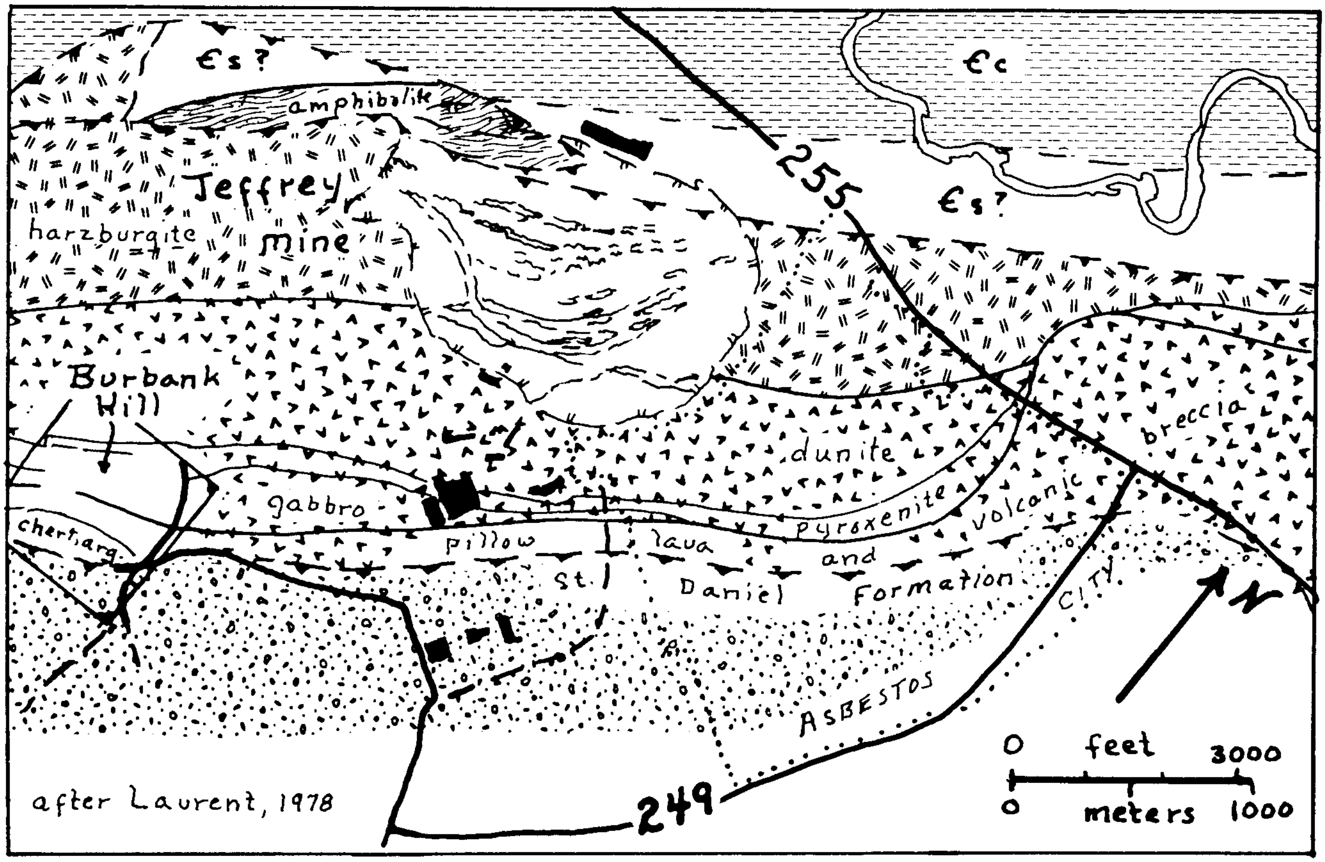


Figure 13. Geology of the Asbestos-Richmond region; Stops 16 and 17. Compiled from Osberg (1965), Globensky (1978), and Lamarche (1972).



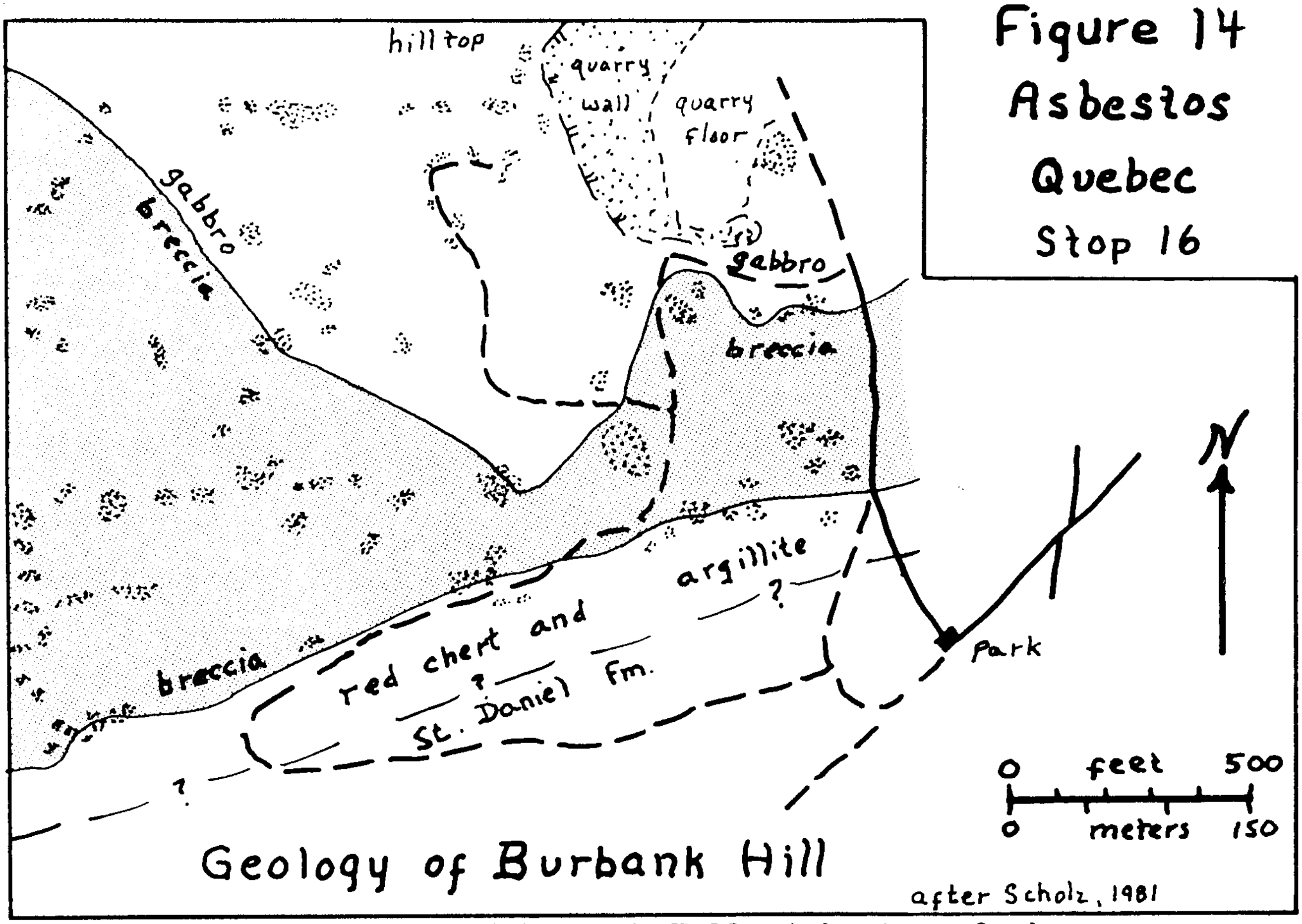


Figure 14. Geology of Burbank Hill, Asbestos, Quebec; Stop 16 (after Laurent, 1978 and Scholz, 1981).

Return to the cars and follow the map (Fig. 13) to Richmond via Danville. Proceed past the Jeffrey Mine to Route 255 in Asbestos. Go west on Route 255 through Danville to Route 116 (approximately 4.8 miles). Proceed south on Route 116 to the intersection with Route 143 just north of Richmond (10 miles). Go right (west) at the intersection following the combined Route 116/143 to the bridge over the St. Francis River. A more detailed road log commences at the bridge.

Stop 17 Roadcut Geology at 40 mph!
Boldfaced mileages show in Figure 13.

0.0 Route 116; on bridge over St. Francis River, Richmond heading west.

1.3 Junction with Route 55. Large road cuts of lower Oak Hill Group near the core of the Sutton Mountain anticlinorium. Proceed southeast on Route 55.

2.7 Outcrops on both side of road of beautifully folded eastward verging "F_2" folds (Osberg, 1965) in the Sweetsburg Formation (= Ottaquechee Formation in Vermont).

3.5 Racine Exit; continue on Route 55.

5.8 Outcrops on both sides of road; Caldwell facies feldspathic quartzites.

6.4 Large outcrops of serpentinite which is the southern continuation of the Asbestos ophiolite visited to the north.

6.9 Large outcrops on both sides of the road include feldspathic quartzites and greywackes similar to the Caldwell facies seen at 5.8 miles. Here, they are interbedded with the St. Daniel Formation. The separation of "Caldwell" and "St. Daniel" on opposing sides of the ophiolite which characterizes the ophiolite belt from Thetford Mines to Asbestos appears to break down to the south.

From 6.9 miles to Windsor Exit, outcrops of undifferentiated Magog Group and of St. Daniel Formation are observed. Continue south to Sherbrooke where Route 55 joins Route 10; proceed west to Exit 121. Take the exit and proceed south on Route 55 to the Vermont border. For those wishing more geology, stop at excellent exposure of Ordovician Ascot volcanic rocks along both sides of the southbound entrance ramp to Route 55 at the Ayers Cliff Exit (approximately 7.8 miles south of Exit 121).

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APPENDIX A: TABLE 1

SELECTED ANALYSES FROM THE QUEBEC APPALACHIAN OPHIOLITES

in wt.%	1	2	3	4	5	6	7	8	9	10
SiO_2	39.93	42.52	34.33	42.11	50.11	47.97	48.07	53.35	51.08	57.74
TiO_2	0.00	1.12	0.00	0.00	0.29	0.04	0.15	1.09	0.07	0.21
Al_2O_3	0.37	16.40	1.04	0.21	1.60	11.21	17.57	14.50	11.60	12.65
Fe_2O_3	4.43	2.65	5.38	3.96	2.36	1.54	2.48	3.84	1.91	3.44
FeO	3.49	8.35	3.03	3.95	3.52	4.81	6.05	6.86	6.70	4.41
MgO	40.62	11.15	40.04	32.91	24.12	16.27	9.94	5.49	13.98	8.71
MnO	0.12	0.19	0.13	0.14	0.11	0.13	0.14	0.17	0.15	0.15
CaO	0.34	13.22	0.00	4.88	14.84	13.18	6.55	4.23	6.91	5.41
Na_2O	0.06	1.05	0.02	0.06	0.20	0.30	2.99	5.12	2.21	4.12
K_2O	0.05	0.19	0.00	0.06	0.01	0.09	0.96	0.16	0.20	0.08
P_2O_5	0.00	0.11	0.00	0.00	0.01	0.00	0.00	0.07	0.02	0.02
H_2O+	8.65	2.50	13.41	10.21	2.82	3.86	4.17	3.82	3.91	2.54
H_2O-	0.82	0.02	0.52	0.44	0.18	0.09	0.26	0.20	0.30	0.08
CO_2	nd	nd	nd	nd	nd	nd	0.32	0.63	0.42	nd
Total	98.88	99.47	97.90	98.93	100.17	99.47	99.65	99.53	99.49	99.56
in PPM										
Cr	2930	563	8210	2800	2300	683	-	119	1061	410
Ni	2193	208	1920	800	306	203	25	28	277	175

Lower Unit:

1. Harzburgite, about 60 percent serpentinized, tectonite; sample 2-05772, Black Lake.
2. Garnet-bearing amphibolite, metamorphic aureole; sample 6-31873, Belmina Ridge, Thetford Mines complex.

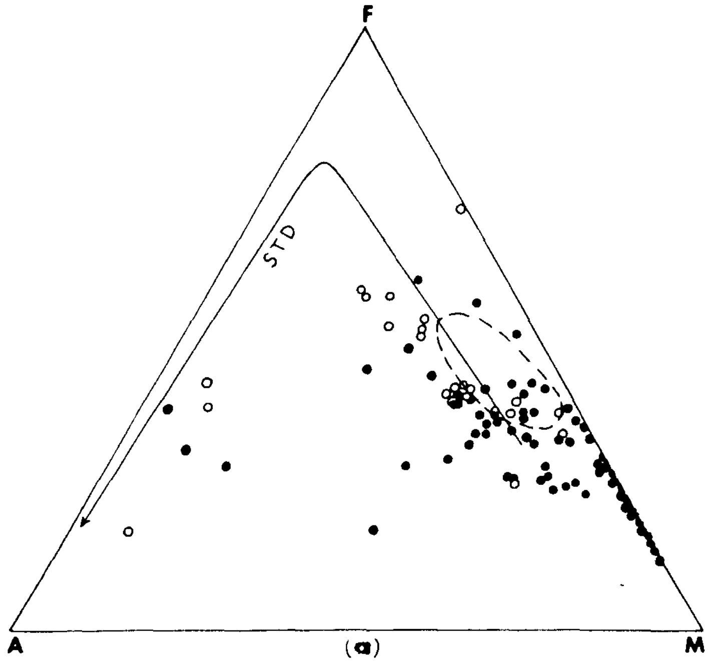
Upper Unit:

3. Chromite-bearing dunite, entirely serpentinized, cumulate; sample 70-26772, Provençal Hill, Lake Caribou, Thetford Mines complex.
4. Wehrlite with olivine entirely serpentinized, cumulate; sample 27-27772, East Lake, Thetford Mines complex.
5. Clinopyroxenite, cumulate; sample 4-27772, East Lake, Thetford Mines complex.
6. Gabbro, partly amphibolitized, cumulate; sample 15-27772, East Lake, Thetford Mines complex.
7. Metagabbro, fine-grained, non-cumulate; sample 36-27772, East Lake, Thetford Mines complex.
8. Metatholeiite, average of 7 analyses from East Lake, Lower Volcanic Group; Thetford Mines complex (see Laurent and Hébert, 1977).
9. Olivine metabasalt, average of 5 analyses, Lower Volcanic Group; sample A from Mount Adstock, Thetford Mines complex (see Seguin and Laurent, 1975).
10. Meta-andesite, Upper Volcanic Group; sample 18-7873, Columbe Lake, Thetford Mines complex.

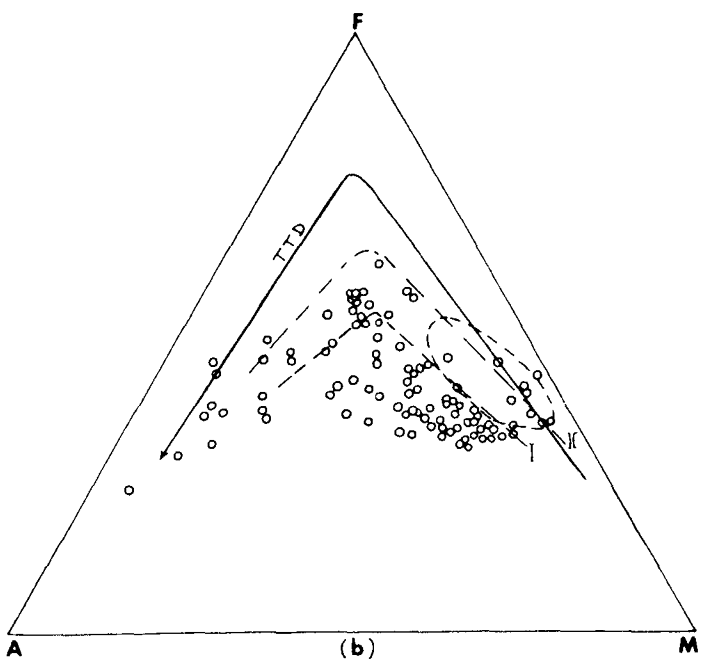
SOURCE: Laurent, Hébert and Hébert, 1979

APPENDIX B: Figure 15

MFA diagrams (after Laurent and others, 1980).



(a). MFA diagram for the ultramafic and gabbroic cumulates (dots) and diabase dykes (open circles). For comparison, the Stillwater trend of differentiates (STD) is indicated. The field of the high-Mg low-Ti pillow lavas (parental magma?) is encircled.



(b). MFA diagram for the pillow lavas. For comparison, the theoleiitic trend of differentiation (TTD) is indicated. Two magmatic suites are distinguished: I, theoleiitic, East Lake type; II, high-Mg low-Ti basaltic, Mount Adstock type.

October 26, 1974

GEOLOGY OF THE GUILFORD DOME AREA, BRATTLEBORO QUADRANGLE, SOUTHEASTERN VERMONT

VERMONT GEOLOGY VOLUME 4

VGS GUIDEBOOK 1

FIELD TRIP GUIDE B

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GEOLOGY OF THE GUILFORD DOME AREA, BRATTLEBORO QUADRANGLE, SOUTHEASTERN VERMONT

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INTRODUCTION

The Guilford dome lies within the broad outlines of the regional Connecticut Valley - Gaspé synclinorium. This synclinorium, principally underlain by Siluro-Devonian rocks, separates the Oliverian gneiss-cored domes of the Bronson Hill anticlinorium to the east from the Green Mountain anticlinorium to the west. The Guilford dome is part of a belt of domes that extends southward from east-central Vermont to Connecticut, west of the Connecticut River, analogous to but more widely spaced than the domes of the Bronson Hill anticlinorium. Large recumbent folds are found in the strata mantling these domes in eastern Vermont (Doll and others, 1961; Rosenfeld, 1968). The Standing Pond Volcanics is an important marker unit outlining many of these recumbent folds and domes. The axial surfaces of the recumbent folds have been arched by the later doming. The arcuate, closed, double band of the Standing Pond Volcanics around the southern end of the Guilford dome (Fig. 1) outlines such a refolded recumbent fold. One of the main purposes of the field trip is to investigate this fold and the proposed east-facing recumbent anticline above it. Other stops will be made to view the Black Mountain Granite, an important key in determining the time of deformation; the Waits River Formation in the exposed core of the dome; and the Putney Volcanics, which separates the "Vermont" and "New Hampshire" sequences.

This field excursion is similar to that taken during the 1972 N.E.I.G.C. (Hepburn, 1972b). For a more complete description of the geology of the area and more recent references, the reader is referred to Hepburn and others, 1984.

ACKNOWLEDGMENTS

Geological mapping of the Guilford dome area was part of a Ph.D. thesis at Harvard University under the direction of Professors M.P. Billings and James B. Thompson, Jr., whose help the author would particularly like to acknowledge. I would also like to thank the many persons who assisted during the course of the field work. Financial assistance of the Reginald and Louise Daly Fund, Harvard University, is gratefully acknowledged.

STRATIGRAPHY

Please refer to Skehan and Hepburn (1972) and Hepburn and others (1984) for descriptions of the stratigraphic units and for regional correlation charts. Units pertinent to this trip are summarized below.

MIDDLE ORDOVICIAN

Barnard Volcanic Member, Missisquoi Formation

4000-8000 feet thick. Massive porphyritic and non-porphyritic amphibolites, feldspar-rich gneisses, and layered gneisses.

SILURIAN

Shaw Mountain Formation

(Russell Mountain Formation of Hepburn and others, 1984). 0-20 feet thick. Quartzite and quartz-pebble conglomerate, hornblende fasciculite schist, amphibolite, and mica schist.

Northfield Formation

1000-2500 feet thick. Gray mica schist with abundant almandine porphyroblasts, minor impure quartzite and impure punky-brown weathering marble.

Waits River Formation

3000-7500 feet thick. Mica schist (phyllite at lower metamorphic grades) and calcareous mica schist with abundant interbeds of punky-brown weathering, impure marble; thin interbeds of micaceous quartzite.

Quartzitic member: feldspathic and micaceous quartzite interlayered with muscovite schist.

Standing Pond Volcanics

0-500 feet thick. Medium-grained amphibolite and epidote amphibolite; garnet-hornblende fasciculite schist.

Eastern band: plagioclase-biotite-hornblende-quartz granulite and gneiss.

Gile Mountain Formation

2500-5000 feet thick. Light gray to gray, micaceous and feldspathic quartzite and mica schist; gray, fine-grained phyllite and slate with interbedded, thin micaceous quartzite; and rare impure marble.

Marble member: black phyllite with interbeds of punky-brown weathering, impure marble and micaceous quartzite.

Putney Volcanics

0-400 feet thick. Light, greenish gray phyllite; buff to light brown weathering feldspathic phyllite; thin beds of feldspathic granulite; and minor gray slate.

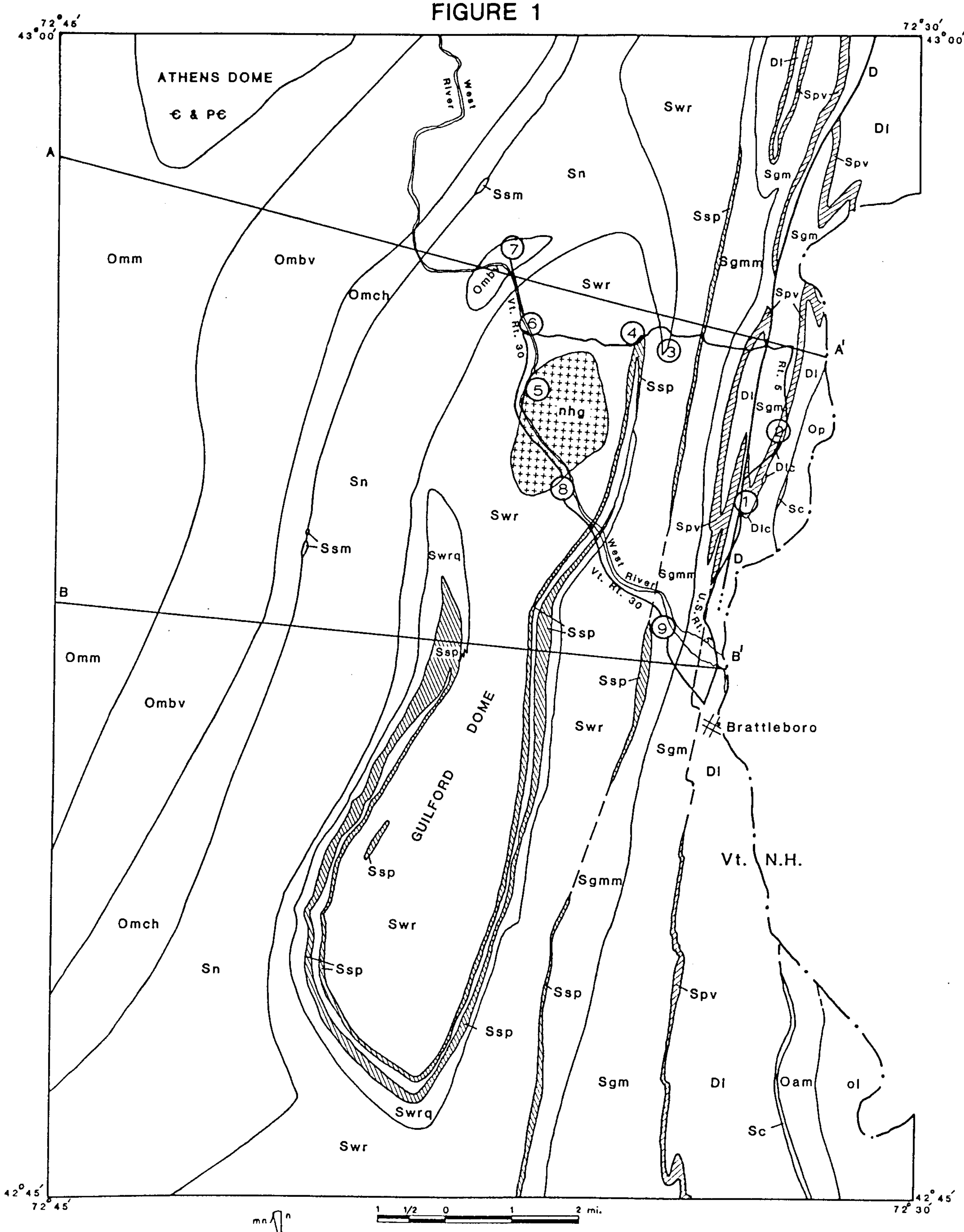
DEVONIAN

Littleton Formation

5000-6000 feet thick. Gray slate or phyllite with interbedded quartzite.

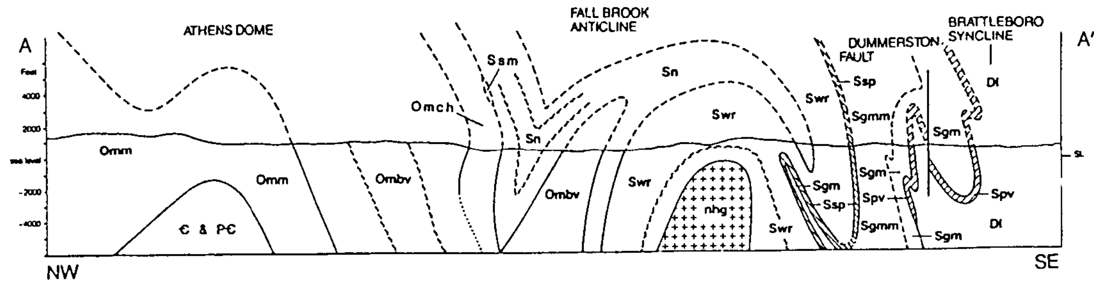
Conglomeratic member: lenses of polymict conglomerate with a gray slate matrix; pebbles abundant to scarce.

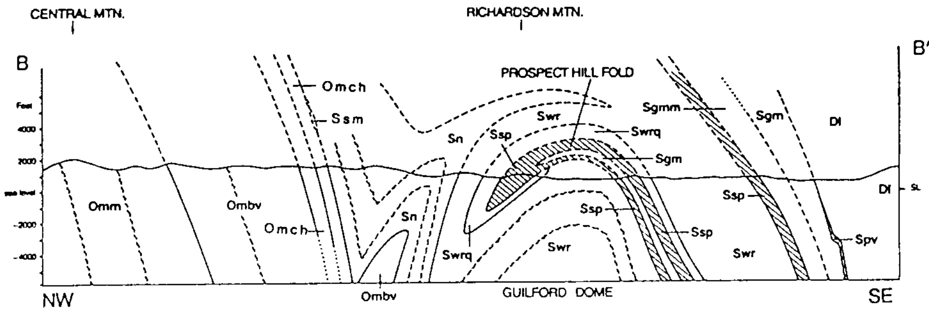
FIGURE 1



GEOLOGIC MAP OF THE GUILFORD DOME AREA, SE VERMONT

B2





LEGEND FIGURE 1

METAMORPHIC ROCKS

Dl	LITTLETON FM.	Swr	WAITS RIVER FM.		
Dlc	LITTLETON FM., congl. mbr.	Sn	NORTHFIELD FM.		
Spv	PUTNEY VOLCANICS	Ssm	SHAW MOUNTAIN FM.	Sc	CLOUGH QUARTZITE
Sgm	GILE MOUNTAIN FM.	Omch	MISSISOUOI FM., Cram Hill Mbr.	Op	PARTRIDGE FM.
Sgmm	GILE MT. FM., marble mbr.	Ombv	MISSISOUOI FM., Barnard Volc. Mbr.	Oam	AMMONOOSUC VOLC.
Ssp	STANDING POND VOLC.	Omm	MISSISOUOI FM., Moretown Mbr.		
Swrq	WAITS RIVER FM., qtzt. mbr.				

PLUTONIC ROCKS

nhg	NEW HAMPSHIRE PLUTONIC SERIES Black Mt. Granite
ol	OLIVERIAN PLUTONIC SERIES

Fault, D on Downthrown side

Field Trip Route & Stop

Geology and Cross Sections Modified after

Hepburn, Trask, Rosenfeld, and Thompson, 1984

EARLY TO MIDDLE DEVONIAN INTRUSIVE ROCKS

Black Mountain Granite

Medium-grained two-mica granodiorite, correlated with the New Hampshire Plutonic Series (Billings, 1956).

The Putney Volcanics (Stops 1 and 2) consists of a belt of rocks that were formerly included in the Standing Pond Volcanics (Doll and others, 1961; Trask, 1964). Since proper correlation of these rocks has not yet been established, Hepburn (1972a) and Trask (1980) have designated them as a separate formation.

No definitive evidence for the facing of the Waits River, Standing Pond, and Gile Mountain formations has yet been found in southern Vermont. However, Fischer and Karabinos (1980) reported good stratigraphic topping evidence near Royalton, Vermont, that indicates the Gile Mountain is younger than the Waits River Formation. Thus the sequence, oldest to youngest, of Waits River, Standing Pond, and Gile Mountain, as shown on Figure 1 is favored, although other possibilities can not be ruled out.

Good stratigraphic topping evidence has been found in the Brattleboro area at several sites within the Putney Volcanics and at its contact with the Littleton Formation (Hepburn and others, 1984). This evidence, based on small cross-bedded sequences, consistently indicates that the stratigraphy gets younger to the east, i.e., that the Littleton overlies the Putney.

STRUCTURAL GEOLOGY

The major tectonic features in the Guilford dome area formed during the Acadian orogeny, between the end of sedimentation in the Early Devonian and the crystallization of late, unoriented, coarse muscovite crystals in the Black Mountain Granite 377-383 m.y. ago (Naylor, 1971). Late normal faulting and possibly some minor folding occurred during the Triassic. The two major stages of deformation in the area include: (1) the development of large recumbent folds, followed by (2) the rise of the Guilford dome.

The doubly-closed loop of Standing Pond Volcanics around the southern part of the Guilford dome outlines the Prospect Hill recumbent fold, named for exposures at the hinge (Stop 3). The Gile Mountain Formation forms the core of the fold. Originally the Prospect Hill fold had a subhorizontal axial surface and a hinge striking northeast-southwest. The subsequent doming about a roughly N-S axis arched the axial surface of the recumbent fold, so that now the hinge plunges moderately northeast and southwest away from the axial trace of the Guilford dome. An early, tight, now overturned, steeply east-dipping synform must lie between the Standing Pond bands in the doubly-closed loop and a third band lying to the east of the Guilford dome (Fig. 1). The hinge line where the Standing Pond rocks cross the axial surface of this synform is not seen in the Brattleboro area and is presumably buried. This synform, the Northfield Formation around the north end of the Guilford dome, and the Fall Brook anticline which exposes the Barnard Volcanics, are interpreted as the upper (anticlinal) portion of the Prospect Hill fold (Fig. 1, Cross-section A).

It is very likely that the Prospect Hill fold is continous with the Ascutney sigmoid in the Saxtons River quadrangle to the north (Rosenfeld, 1968; Doll and others, 1961). If this is true, the hinge of the Prospect Hill fold must turn more northerly a short distance north of Stop 3.

The Guilford dome, which occupies much of the central portion of the Brattleboro quadrangle (Fig. 1), is a large, elliptical, doubly-plunging anticline formed during the second major stage of deformation. The Waits River Formation forms the exposed core of the dome. The foliation dips away in all directions from the axial trace, which strikes slightly east of north and plunges moderately to the north and south at the ends of the anticline. The axial surface of the dome dips very steeply to the west. A small depression in the exposed central portion of the dome divides it into a northern and southern lobe. The axial trace of the dome is closer to its eastern side. Here, the foliation has steep dips a short distance east of the axial trace. Dips are more gentle to the west. Bedding with a schistosity parallel to it has been arched by the dome.

It is likely that the two major stages of deformation were not greatly separated in time.

MINOR FOLDS

Minor folds of at least five different stages are present in the Guilford dome area and the Brattleboro syncline to the east of the dome. These stages of minor folding are summarized below:

- F1. Small isoclinal folds in layering, with schistosity developed parallel to the axial surfaces (Stop 3).
- F2. Tight to isoclinal folds congruous with the large-scale recumbent folding (Prospect Hill fold). These fold the schistosity and the F1 folds. Weak to moderate axial-planar cleavage. Plunge moderately NE. or SW.
- F3. Open folds, particularly west and south of the Guilford dome. Excellent slip-cleavage developed parallel to the axial surfaces. The axial surfaces generally strike NE. and dip steeply NW. The hinges plunge moderately NE. Excellent crinkle lineations occur at the intersection of this slip-cleavage and the schistosity surfaces in the pelitic rocks.
- F4. Open folds, buckles or warps in the foliation that are of one or more generations and fold the slip-cleavage.
- F5. Large open folds found only in the eastern part of the area (Fig. 1) that offset the Putney Volcanics with an east-side-north movement. Plunge is moderately to steeply north. Kink bands also found along the eastern part of Figure 1 are the youngest minor folds and may be related to the above F5 folds or may be younger.

METAMORPHISM

A belt of low-grade metamorphic rocks (chlorite zone) occurs in the eastern part of the area and roughly follows the Connecticut River. This low is of regional extent (Thompson and Norton, 1968) and separates terrains of higher metamorphic grade along the Bronson Hill anticlinorium from those in the domes of eastern Vermont. The highest grade of regional metamorphism in the Guilford dome area, staurolite-kyanite zone, is centered on the dome. The peak of metamorphism probably closely followed the doming stage of major deformation. During the early recumbent folding, the grade of metamorphism did not exceed the garnet zone.

ROAD LOGS

Topographic map: Scheduled stops will be in the Brattleboro 15 minute quadrangle, Vermont-New Hampshire. The Geologic Maps of the Brattleboro quadrangle (Hepburn and others, 1984) and of Vermont by Doll and others (1961) are of interest.

Stop 1. Putney Volcanics

Mileage

0.0 At the junction of Routes 5, 9, and 91 north of Brattleboro by Howard Johnson's Restaurant just off Interstate 91 Exit #3, turn left (north) onto Route 5.

0.7 Overpass over I91.

0.9 Brattleboro-Dummerston town line.

1.2 Park in rest and picnic area on the east side of Route 5.

The Putney Volcanics (Hepburn, 1972a) in this area consists of fine-grained, poorly foliated, light greenish gray quartz-plagioclase-muscovite phyllites and granulites with interbedded gray slates. The granulites and feldspathic phyllites weather buff to light brownish gray, characteristic of feldspar-rich rocks. Many of the foliation surfaces have a notable silky sheen. Small, brownish pits where carbonate has weathered out are common. The granulite beds may show a fine lamination. A few lenses of quartz-pebble conglomerate assigned to the Littleton Formation may be seen along Route 5 south of the highway pull-off but are much better developed at Stop 2. The rocks have been metamorphosed to the chlorite zone at this locality.

Continue north on Route 5.

Stop 2. Littleton Formation, Conglomeratic Member

1.4 Outcrop of Putney Volcanics to the east.

1.5 Outcrop of Putney Volcanics to the west.

2.1 Slate quarry in Littleton Formation to the east.

2.3 Park at left (west) side of road in the highway pull-off.

Examine outcrops of gray slate in the Littleton Formation on the east side of Route 5. Then walk 0.1 mile north through woods to an abandoned chicken-yard beside houses to west of Route 5. Outcrops are of the conglomeratic member of the Littleton Formation. The contact of this conglomerate with the Putney Volcanics represents the division between the "Vermont" and "New Hampshire" sequences in this area. The conglomerate contains both quartzite and slate pebbles in a slate matrix. (As this is the best exposure and type locality for the conglomerate, **NO HAMMERING--PLEASE!**). The excess of matrix over clasts in the conglomerate indicates it best fits Pettijohn's (1957) classification as a paraconglomerate. Pettijohn (1957, pp. 265-266) states that:

> "it now seems probable in light of our knowledge of turbidity currents and related mudstones that most of these abnormal conglomerates [the paraconglomerates] are the product of subaqueous mudslides or slurries".

A few small porphyroblasts of light pink garnet occur here. The outcrop is included in the chlorite zone, however, as probe analyses indicate these garnets contain up to 15.9 weight percent MnO. (The garnet isograd has been mapped on the first appearance of almandine in the pelitic rocks.)

Immediately west of the conglomerate in this outcrop, the Putney Volcanics consists of slate with feldspathic granulite interbeds up to 2 feet thick. This stop has become more overgrown in recent years, since the chickens left.

West of the abandoned chicken-yard a sequence of phyllites and feldspathic granulites similar to those at Stop 1 is exposed on the side of the hill.

Return to cars. Continue north on Route 5.

Stop 3. Northfield Formation

2.4 Road junction with dirt road on right. Continue north on Route 5.

2.6 Roger's Construction Co. yard on right (east), possible alternate parking for Stop 2.

2.9 Dutton Pines State Forest.

3.4 Road junction with road to East Dummerston; continue on Route 5. Outcrop of Putney Volcanics to west.

3.8 Road junction. Turn left (west) on road to East Dummerston and Dummerston Center.

4.7 Road junction in East Dummerston; continue straight.

4.8 Junction with road on right; continue straight.

4.9 Outcrop of Waits River Formation.

5.9 Dummerston Center. Turn sharp left (south).

6.0 Park along side of road.

Walk west to outcrops of the Northfield Formation exposed near the hinge area of the recumbent anticline above Prospect Hill fold (see Fig. 1). The Northfield here is a gray well-foliated mica schist with conspicuous garnet porphyroblasts and fewer porphyroblasts of biotite and staurolite. A few thin interbedded quartzites are also present.

Turn around; return north to Dummerston Center.

Stop 4. Hinge of Prospect Hill Fold, Waits River Formation and Standing Pond Volcanics.

6.1 Dummerston Center. Turn left (west) on paved road past the fire station.

6.5 Park in road pull-off on north side of the road just before the curve.

The Standing Pond Volcanics outline the north-easterly plunging hinge of the Prospect Hill recumbent fold at this locality (Fig. 1). A 1/2 mile traverse will be made around the hinge, following the contact between the amphibolites of the Standing Pond Volcanics and the schists, calcareous schists, and impure marbles of the Waits River Formation. This traverse presents an excellent opportunity to view a well-exposed hinge of a major recumbent fold. The contact is sharp and is easy to follow. The traverse starts just east of the pull-off near a very small creek along the eastern contact of the Standing Pond Volcanics. Follow this contact to the north and around the northeasterly plunging hinge of the recumbent fold, which closes on the lower south-facing slopes of Prospect Hill. Continue along the contact southward (now the western contact of the Standing Pond with the Waits River). The paved road is encountered again 1/4 mile west of the starting point.

Particular note should be made of the minor folds during the traverse. The most common folds are the F2 generation, those formed congruously with the recumbent folding. These plunge NE and show a reversal in drag sense around the hinge. A few F1 minor folds that pre-date the recumbent folding, have the principal schistosity parallel to their axial surfaces, and are refolded by the F2 folds, are visible in outcrops near the road.

If time permits, climb Prospect Hill for an excellent view from the open summit (perhaps lunch). **Please be particularly careful on this traverse** with litter and the indiscriminate use of **hammers.**

Return to cars; proceed west on paved road.

Stop 5. Black Mountain Granite

6.7 Outcrops of the Standing Pond Volcanics in the hinge of the Prospect Hill recumbent fold.

6.8 Contact of the Standing Pond Volcanics with the Waits River Formation.

6.9 Junction with dirt road to south; continue straight on paved road.

7.4 Outcrop of aplitic dike associated with the Black Mountain Granite.

7.8 Junction with road from right (north); continue straight.

8.5 Road junction; take sharp left onto dirt road.

9.3 Park by abandoned quarry buildings and follow path east to the abandoned Presbury-Leland granite quarry.

The Black Mountain Granite is a late synorogenic to post-orogenic two-mica granodiorite correlated with the New Hampshire Plutonic Series (Billings, 1956). Note the weak foliation produced by the alignment of the fine-grained micas. Coarse, unoriented muscovites that are younger than this foliation have been dated by Naylor (1971) from this locality. He obtained Rb/Sr ages of 377 m.y. and 383 m.y. for these muscovites, which sets a minimum age for the pluton as late Early to early Middle Devonian.

West- to northwest-dipping sheeting is well exposed in the quarry walls. Note particularly the increased thickness of the individual sheets with depth.

Stop 5a.

Walk west from the quarry to the banks of the West River. The contact of the granite body with the surrounding Waits River Formation is well exposed here. Dikes and sills of granite and aplite are numerous within a few hundred feet of the contact and may indicate a stoping mechanism for the emplacement of the granite pluton. The dikes cross-cut bedding and the principal schistosity. Some have a weak foliation roughly parallel to the regional schistosity but clearly post-date the major deformation. The country rocks near the granite have been altered by contact metamorphism, in addition to being regionally metamorphosed to the staurolite-kyanite zone.

Return to cars; turn around and retrace route north to the main road.

Stop 6. Waits River Formation

10.1 Junction with paved road; continue straight (north).

10.2 Park just beyond the entrance to the covered bridge, heading north.

Outcrops typical of the Waits River Formation in the center of the Guilford dome are seen along the east bank of the West River. The rocks are interbedded impure marbles, calcareous mica schists, and mica schists. Most of the minor folds present here are assigned to the F2 stage and developed congruously with the large-scale recumbent folding. They were refolded into their present attitude by the rising of the Guilford dome.

Return to cars; proceed straight (north) on the dirt road along the east side of the West River.

Stop 7. Barnard Volcanics

10.7 Junction with road to right; continue straight.

11.2 Park along the road above the east end of the old West Dummerston Dam. Climb down the steep bank (**use caution**) to the west end of the now abandoned dam.

The Middle Ordovician Barnard Volcanics are exposed here in the center of the Fall Brook anticline, which forms the core of the proposed recumbent anticline above the Prospect Hill recumbent fold (Fig. 1). At this stop the rocks include amphibolites and felsic gneisses. Minor amounts of rusty-weathering schist are present along with the Barnard in this anticline but have not been designated separately on Figure 1.

Turn around; retrace route south to the covered bridge.

Stop 8. Waits River Formation Altered by Contact Metamorphism.

12.2 Covered bridge; turn right; cross the bridge. At the west end, turn left (south) onto Route 30.

12.9 West Dummerston Village. Note Black Mountain and the granite quarry to the east across the West River.

13.3-13.6 Outcrops of the Waits River Formation.

13.8 Iron bridge to left; junction of road to the right. Continue straight on Route 30. Outcrops of granite in the brook to the west.

15.2 Park at the side of Route 30 by the large road-cut on the right (west).

The Waits River Formation in this outcrop is near the contact of the Black Mountain Granite. Calc-silicates (particularly actinolite and diopside) are well developed in the impure marble beds. Diopside has not been observed in the Waits River Formation of the Guilford dome area outside of the contact aureole of the Black Mountain Granite.

Continue south on Route 30.

Stop 9. Gile Mountain Formation, Marble Member

16.8 Roadmetal quarry in the Waits River Formation to the west.

17.0 Outcrop of Waits River Formation.

17.7 Park at left in the pull-off under the I91 overpass.

Outcrops under the overpass are fairly fresh exposures of the marble member of the Gile Mountain Formation, metamorphosed to the biotite zone. The impure marble beds (with their distinctive punky-brown weathering rinds) similar to those in the Waits River Formation are interbedded with phyllites. The percentage of micaceous quartzite beds is fairly high here (approximately 15 percent), as is typical of this member.

END OF FIELD TRIP

Continue south 1.5 miles to Brattleboro for junctions with the major highways.

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August 21, 1976

THE CROWN POINT SECTION, NEW YORK

VERMONT GEOLOGY VOLUME 4

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VGS GUIDEBOOK 1

FIELD TRIP GUIDE D

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THE CROWN POINT SECTION, NEW YORK

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INTRODUCTION

GEOLOGIC SUMMARY

The Crown Point section in New York is interesting for several reasons beyond the scenic and historic attributes. Many of the strata are rich in fossils (Raymond, 1902) (see Appendix A); there is a variety of environments of deposition displayed by fossils and sedimentary features; and the section as a whole records the onset of rapid crustal subsidence at the start of the Taconic orogeny.

Beds strike northeast and dip about 7° NW. The stratigraphic section consists of 120 meters of limestones and dolostones; most of the lower third is covered in the route we will take. On weathered surfaces, dolostone is colored cream to tan to brown; limestone is light to medium gray.

Strata within the section are seen at localities identified by letters A to L (Figs. 1, 2), following Baldwin (1980). The section represents the Chazy Group, the Orwell Limestone, and the Glens Falls Limestone, all of Medial Ordovician age. The Chazy strata were deposited about at sea level; the Orwell was deposited in the photic zone; and the Glens Falls was deposited in somewhat deeper water, with essentially no shallow-water characteristics.

Parenthetically, the Orwell is properly a Vermont term rather than a New York term, but its massive and poorly bedded character sets it aside from the underlying limestone-dolostone bedding of the Chazy and from the overlying well-bedded Glens Falls. Figure 2 uses stratigraphic terminology of Fisher (1977) and it shows New York equivalents of the Orwell (Lowville, Watertown, Selby, Napanee).

STATE HISTORIC SITE

The location, at the north end of Crown Point peninsula (Fig. 1) is a State Historic Site. As a result, the grounds are very well maintained (though there are some patches of poison ivy off the main paths). The Visitor Center has restrooms and a brief but effective slide show on the history of the area in the late 1700's. The Site's hours of operation are:

SUMMER: June through 3rd week in October,
Wed. through Sun.: gate open 9 am to about 7 pm;
Visitor Center (restrooms) open
10 am to 5 pm, Wed. through Sat.;
1 pm to 5 pm Sun.
WINTER: Last week in October through May:
gate open weekdays only, 8 am to 4:30 pm;
Visitor Center (restrooms) closed.
SPECIAL ARRANGEMENTS may be requested in advance:

Crown Point Historic Site
R.D. #1, Box 219
Crown Point, New York 12928
(518+597-3666).

Present policy is that the site may be visited even when the gate is closed: leave cars outside gate (**DO NOT BLOCK GATE**) and walk in. One caution is that **no hammers** are to be used and **no samples** may be collected. The many hundreds of geologic visitors have honored this over the years and so the outcrops are essentially pristine. It is helpful and evidently not objectionable to use chalk to circle fossils for the aid of others.

MICROFACIES ANALYSIS

Thin sections from the stratigraphic sequence at Crown Point were point counted (200 grains per slide) for constituent composition analysis. Included in this analysis were: spar cement, carbonate mud, dolomite and quartz/terrigenous mud abundance, and allochem abundance (pellets, pelmatozoans, brachiopods, trilobites, algae, bryozoa, gastropods, corals, sponge, intraclasts and unidentified skeltal fragments). Based on the results of this study, six lithologies were recognized: (1) subequal amounts of quartz, dolomite, allochems, micrite, and spar cement; (2) recrystallized limestone; (3) dolomite with variable amounts of quartz and allochems; (4) quartz arenite; (5) variable amounts of allochems, carbonate mud matrix and spar cement with little quartz and dolomite; (6) carbonate mud and skeletal fragments. The distinguishing characteristics of each will be briefly discussed and environmental interpretations presented. The raw data for the constituent analysis are presented in Table 1 and Figure 3.

LITHOLOGY 1

This microfacies is composed of subequal amounts of all constituents: carbonate mud, spar cement, allochems, quartz and dolomite. The allochems are dominantly algae, and pellets with skeletal fragments uncommon. Much of the micrite present has aggraded to neomorphic spar. Spar cement is present as shelter cement, intraparticle and interparticle cements. Stylolites are common and quartz and terrigenous muds are concentrated along these seams. This microfacies is present in the lowest and middle stratigraphic horizons at Crown Point (0.5 to 4.8 meters and 66 meters above the base).

LITHOLOGY 2

Lithology 2 is dominantly composed of spar cement which has recrystallized allochems and aggraded micrite to fine-grained spar. The resultant mosaic of coarse spar crystals has destroyed all original textural relationships. Micrite is present but is only found as coatings on allochems (micrite rims). Spar cement is present between clots of algae. A later generation of spar has overgrown skeletal fragments. This lithology is present at two stratigraphic positions, 24 and 116 meters. The relative abundance of identifiable constituents suggests that recrystallization is not fabric selective but represents different diagenetic conditions.

LITHOLOGY 3

Lithology 3 is a dolostone with variable amounts of quartz disseminated throughout. Dolomite is present as small equant cloudy rhombs, occasionally exhibiting zonations. Subangular quartz grains are 0.4 to 0.2 mm in diameter (medium to fine sand). No allochems are present. Because of the absence of any diagnostic constituents or sedimentary structures, the environment of deposition of this facies cannot be determined with any certainty. This microfacies is found at horizons from 45 to 54 meters.

LITHOLOGY 4

Lithology 4 is a quartz arenite composed of subrounded grains of poorly sorted (fine to very coarse sand) quartz. Grains of zircon and potassium feldspar make up approximately 2 percent of the sandstone. The high degree of compositional maturity and rounding of the quartz suggests a multicycle history of the grains (derived from another sedimentary rock). The relatively poor sorting indicates little reworking at the final site of deposition. This microfacies is found at only one horizon, 75 meters. It is important to note that above this horizon quartz grains within limestones are absent.

LITHOLOGY 5

This lithology occurs between horizons at 82 meters to 95 meters in the stratigraphic section. The microfacies is composed of variable amounts of micrite, spar cement and allochems. Texturally this facies would range from wackestone to packstone. This facies is similar to lithology 1, however dolomite and quartz grains are absent and allochem composition is different; overall faunal diversity is higher than in lithology 1 and in particular, algae are less abundant. This evidence suggests microfacies 5 was deposited in deeper water, probably further from any terrigenous sources.

LITHOLOGY 6

The final lithology is composed of carbonate mud and skeletal fragments and little spar cement. Texturally this facies is a wackestone. Spar cement is present only as shelter cements and interparticle cement within interstices of allochems such as gastropods and bryozoa. This facies is also characterized by a greater diversity of skeletal fragments with bryozoa, trilobites and brachipods more abundant than elsewhere in the stratigraphic section. This lithology occurs near the top of the stratigraphic sequence (105-116 meters) and overlies lithology 5. This stratigraphic position, along with the increasing micrite content and absence of algae, suggests increasing water depths.

ENVIRONMENTAL SUMMARY

Based on microfacies analysis of samples from the Crown Point, Valcour, Orwell and Glens Falls formations from Crown Point, this section is interpreted to represent a generally transgressive sequence. Lithologies 1 through 4 can be interpreted as representing sediments deposited in a lateral facies mosaic of shallow subtidal conditions. Evidence of a peritidal origin (mudcracks, planar or LLH stromatolites) is not present; however, the abundance of terrigenous detritus (sand and mud) and the presence of herringbone cross stratification suggests a position proximal to a strandline in shallow water, possibly experiencing tidal currents. Microfacies 5 and 6 represent a transgressive sequence of progressively increasing water depth. The stratigraphic sequence is capped by a recrystallized limestone which contains no bathymetric indicators. If these environmental interpretations are correct, the stratigraphic distribution of the microfacies suggests that environmental conditions were relatively stable within the same bathymetric position throughout the basal 80 meters of section. The remainder of the sequence appears to record progressively increasing water depths.

TECTONIC IMPLICATIONS

Combining the environments of deposition with the time-thickness pattern of sedimentation (Fig. 4), the Crown Point section takes on tectonic meaning. The Chazy sediments were deposited just about at sea level - *Girvanella* and *Maclurites*, dolostones, lime-sands, scour channels. Sedimentation was keeping pace with crustal subsidence. Then, the crust began to subside faster than sediments could accumulate. Orwell was deposited in shallow sub-tidal conditions - two corals, the grazing snail *Maclurites*, and probably the *Stromatocerium*. The Glens Falls was deposited in sub-photic or deep photic conditions because it lacks shallow-water indicators. Elsewhere, the Glens Falls is overlain by as much as 1400 m of shale (the Stony Point Limestone and Iberville Shale) (Baldwin, 1980).

Continental shelf sedimentation of the Champlain Lowlands began in the Early Cambrian and continued through deposition of the Chazy. Using the Medial Ordovician time scale of Churkin and others (1977), it is clear that Chazy sedimentation was scarcely 5 meters per million years (m/m.y.). A time-thickness graph (Fig. 4) for this Cambro-Ordovician sequence is a concave-upward curve that shows a continued slowing of crustal subsidence. Assigning 70 percent of the space to the load of sediments (C_s), the remaining 30 percent (C_t) is tectonic subsidence, due to cooling. The C_t curve fits the distal end of the Parsons-Sclater (1977) curve, which properly should be truncated somewhat at its initial end to accommodate crustal extension.

Then, starting with the Orwell, the crustal subsidence is greater than the rate of sedimentation, because the water deepens. The Orwell and Glens Falls accumulated at 30 or 40 m/m.y.; and the thick shales accumulated at 200 m/m.y. (solid-grain thickness) (Baldwin, 1980). This high rate is comparable to the rate of subsidence of the Australian platform entering the Timor trench (600 m/m.y.; Baldwin, 1983).

The Crown Point section fits the picture of a cooling and slowly subsiding continental margin, through Chazy time. Then, the margin began collapsing as it tried to enter a subduction zone to the east, causing water to deepen rapidly. The section is a record that immediately precedes the continent-arc collision that constitutes the Taconic orogeny (Baldwin, 1982).

ACKNOWLEDGMENTS

Middlebury College's geology department began using Crown Point section as a field problem in 1962. Since then, Marshall Kay, Gray Multer,

[Continued on Page D7.]

Opposite page

Figure 1. Map of Crown Point, New York area.


LAKE CHAMPLAIN
private
K
J
I
quarry
H
G
park
P
Fort St. Frederic
French 1734
N
pier
lighthouse
F
visitor center
E
D
0 500 1000
feet
pavilion
Fort Crown Point
English 1759
C
light infantry redoubt
A
gate
B
Bullwage Bay
CROWN POINT
N.Y.
bb 4-85

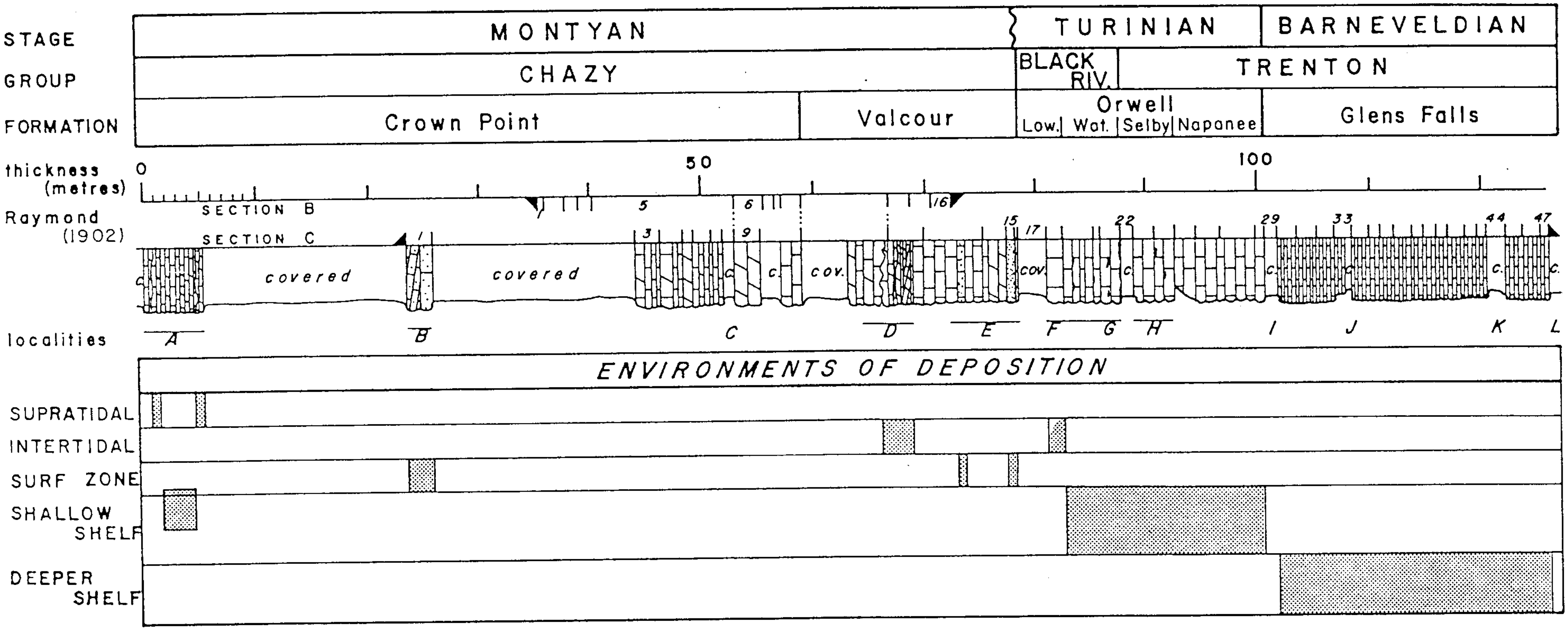

Figure 2. Columnar section of strata in Crown Point area.

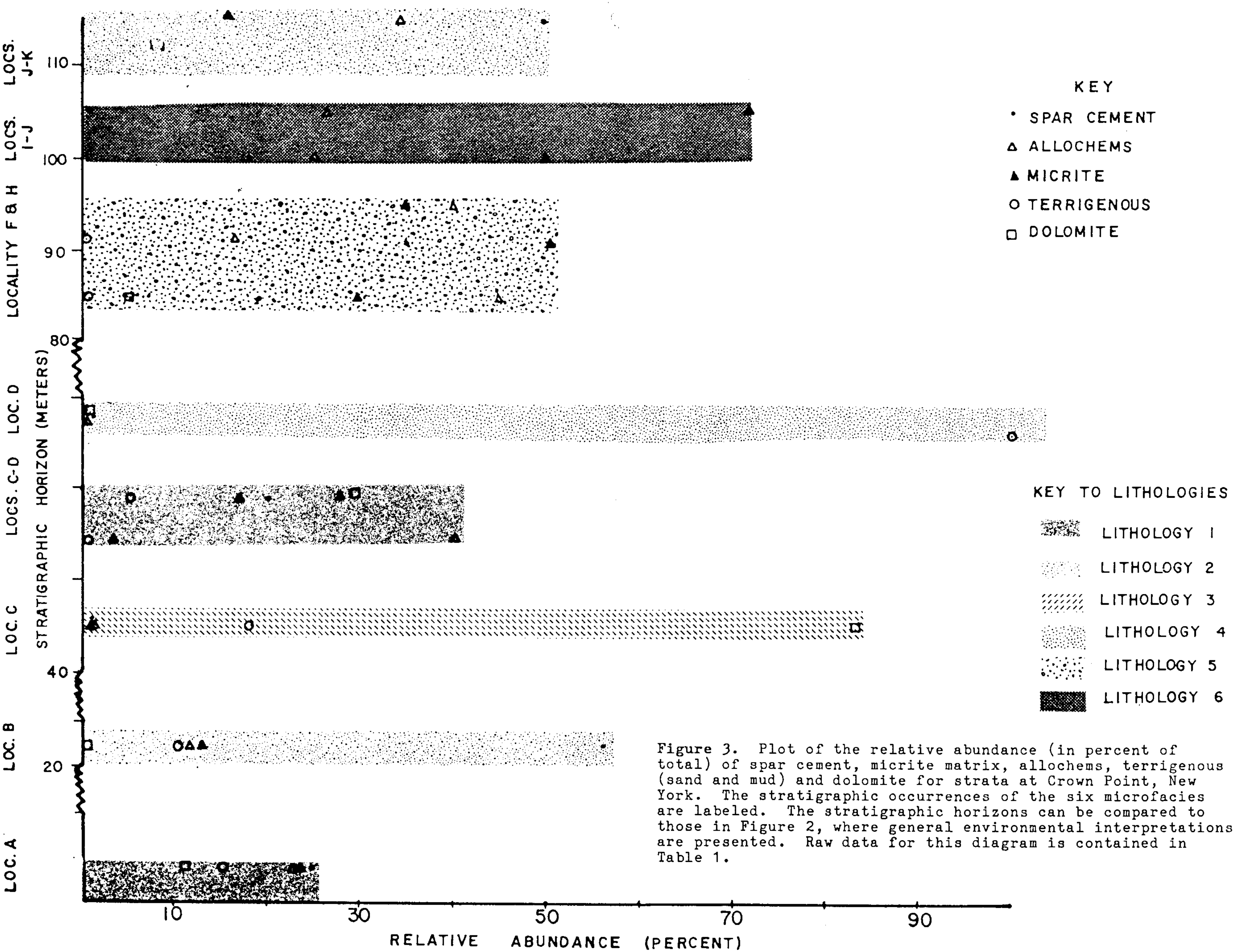

Figure 3. Plot of the relative abundance (in percent of total) of spar cement, micrite matrix, allochems, terrigenous (sand and mud) and dolomite for strata at Crown Point, New York. The stratigraphic occurrences of the six microfacies are labeled. The stratigraphic horizons can be compared to those in Figure 2, where general environmental interpretations are presented. Raw data for this diagram is contained in Table 1.

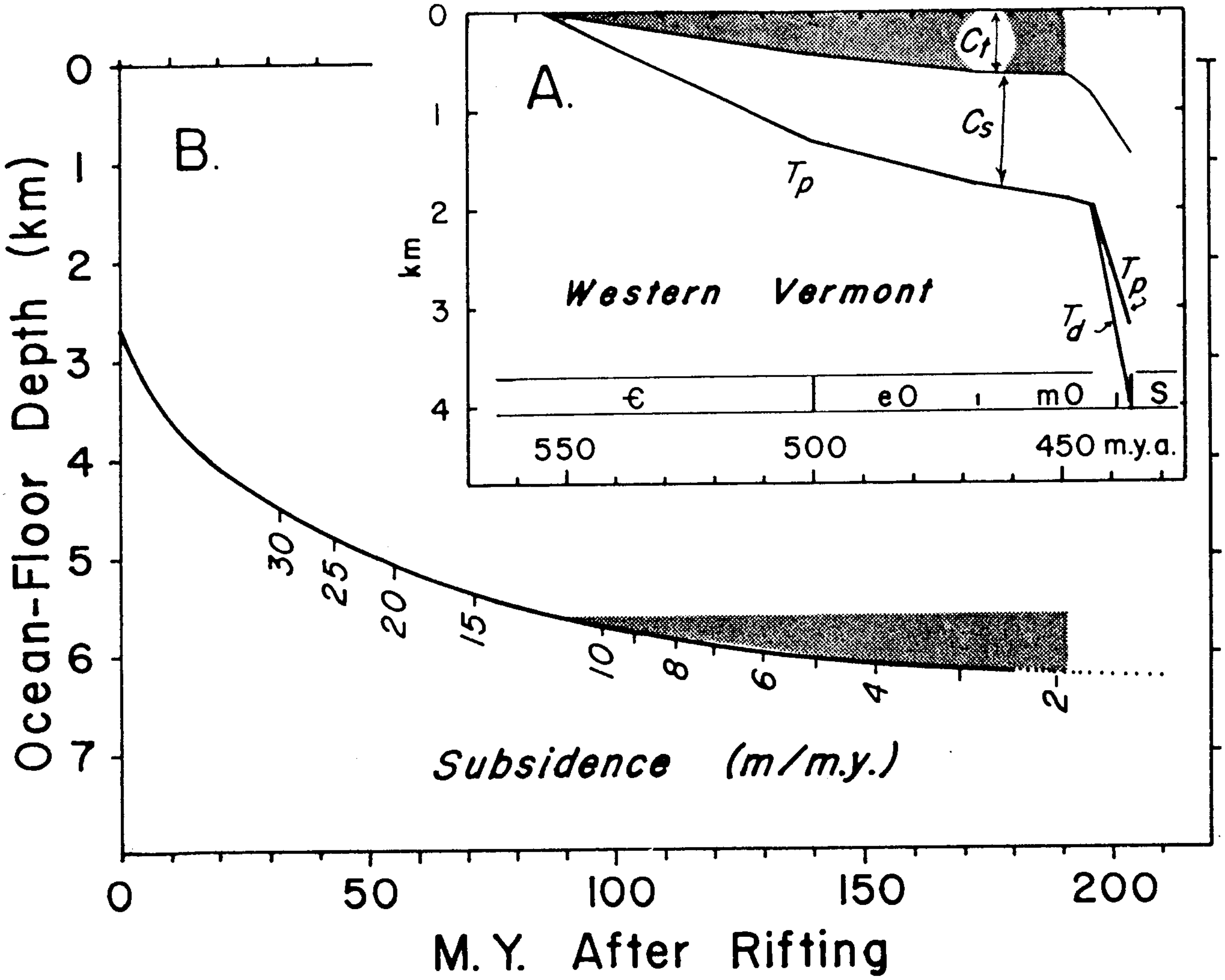

Figure 4. Time-subsidence curve for Champlain Lowlands section.
T_d, thickness at deposition;
T_p, present thickness;
C_s, crustal subsidence due to load of sediments;
C_t, crustal subsidence due to tectonism (cooling).
Ocean-floor depth curve from Parsons and Sclater (1977).

Charles Pitrat, and E.J. Anderson visited the area with the senior author and offered comments and suggestions on the stratigraphy and ways to interpret the environments of deposition. The Vermont Geological Society had a field trip here in the summer of 1976 (the trip leader arrived late!). Bruce Selleck improved the quality of geologic statements for the present field guide. Throughout, Gregory Furness, Historic Site Manager, has provided active interest and assistance in our work.

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ROAD LOGS

STRATIGRAPHIC SECTION

Localities A to E, Chazy Group

Locality A Light infantry redoubt east of N.Y. 8

Park car on loop road past gate into the Historic Site. Please do not climb on the walls of the outpost fort.

About 6 meters of wackstone limestones with dolomite laminae are exposed. Textures range from lime-mud with fossils and fossil fragments to a bed that has 1 cm clasts and was probably a storm deposit. Many of the limestone beds contain large (1 to 2 mm) black rounded grains of calcite. Some of these are the core of oncolites formed by the algae *Girvanella*, which are abundant on the vertical wall and on bedding surfaces near the highway. A few large *Maclurites*, and several straight nautiloids are present. Less conspicuous fossils include brachipods, bryozoans, and trilobite fragments. In the lowest beds, there are cream-colored dolomitized burrows.

The sediments were evidently deposited in very shallow to intertidal waters. *Maclurites* may have grazed on the algae or perhaps were sedentary deposit feeders. Their presence suggests water only a meter or so deep, and the algae similarly speak to very shallow water, close enough to a strandline to supply terrigenous detritus. Dolomite laminae suggest an environment in or just above tidal the range. The nautiloids were swimmers and probably became stranded.

Locality B First ledge on road into Historic Site

The strata underlying the covered interval between A and B are nearly 20 m thick; the same is true for the covered interval between B and C.

This is a cross-bedded oolitic lime-sand with scattered quartz grains. It is about 2 meters thick. Toward the northeast, along this low ridge, there are laminae where quartz grains are concentrated; also, there are pressure-solution stylolites in the highway cut.

Rocks from this interval reveal a high degree of recrystallization. Carbonate mud (micrite) is less abundant than in underlying horizons. Most allochems have been recrystallized and are unidentifiable. *Girvanella* is still present, however. Texturally, these rocks would be termed crystalline limestones, as original grain-matrix-cement relationships are destroyed. The decreasing percentage of micrite does suggest increasing energy levels capable of winnowing away the carbonate. This interpretation is supported by outcrop evidence of current activity. The bipolarity of the cross-bedding directions suggests tidal currents.

Locality C Park at pavilion

Descend slope southeast of pavilion to see alternating limestones and dolostones. One prominent brown-weathering dolostone extends southwest across the Historic Site road; it has some trilobite fragments. Scattered outcrops from the pavilion to locality D have *Maclurites*.

Rocks in this interval fall into two groupings, those which are almost entirely dolomite in composition and those which are texturally wackestones with dolomite subordinant. Of the former type, dolomite occurs with floating quartz grains and no recognizable allochems. More complete petrography and geochemical analysis would be needed in order to more accurately determine the mode of formation of the dolomite.

Locality D East point of fort, by horizontal water tank

This is the "Flag Bastion" of the Site. Drive cars to regular parking area and return to Visitor Center. Walk up concrete path to horizontal water tank.

Note the alternating "ribbons" of limestone and dolostone in a 3 m face. The dolostone is resistant to weathering, and the limestone is indented. On the adjacent smooth face, the limestone and dolostone can be distinguished by color; the dolostone is cream to tan colored or is darker gray and under the hand lens shows rhombs.

This interval consists of subequal amounts of dolomite rhombs, carbonate mud (micrite) and calcite spar cement. *Girvanella* algae are the most abundant allochem. Texturally the unit is a dolomitic wackestone to packstone. There is a minor component of disseminated rounded quartz grains and terrigenous mud present. The dolomite rhombs are associated with the terrigenous grains and micrite (wackstone) whereas the *Girvanella* are associated with the interparticle spar cement (packstone). These two lithologies have been bioturbated together.

Near the base is an erosional unconformity with 10 or 20 cm relief. Dolomitized burrows are abundant in the lower part; fossil "hash" forms several beds; there is a scour channel near the top; and in the upper half meter the dolostone contains clasts of limestone. Some clasts are rolled. Evidently, the limestone beds became somewhat indurated and less permeable, whereas the other beds remained unconsolidated and permeable long enough to become dolomitized. The features in this 3 m face are consistent with an origin on a tidal flat.

Walk southwest along the fort's moat, following these beds along strike; the erosional unconformity is a marker. Fossils are restricted to occasional *Maclurites* and burrows. *Maclurites* shells are locally concentrated as a "lag" in what were probably tidal channels. Enter parade grounds at southeast point of fort.

Locality E Parade grounds by barracks

About 1916, gunite was sprayed on the interior walls to protect the walls from deteriorating. Starting in 1976, the N.Y. State Division for Historic Preservation began extensive maintainance, removing loose gunite, replacing rotted stones, and re-pointing some walls.

In the outer wall of the first barracks, note at about eye level the stones that are nearly white-weathering. These are lime-muds from the Lowville, which is exposed at Locality F.

The broad limestone outcrop west of the barracks is a cross-bedded lime-sand with scattered rounded quartz sand. As with beds at Locality B, these beds indicate a shoal within the reach of wave action. Bipolarity of cross-bedding directions suggests tidal currents. The highest beds in this lime-sand have snails and fairly large limestone clasts. There are also "fossils" of a bird, cannon, and soldier.

Westward across the parade grounds there is massive brown dolostone (one of several in the Chazy section), and then a 0.5 m bed of quartzite with grains as large as 3 mm. The quartzite has burrows, a *Maclurites* imprint, and possible large sand waves. This bed must have been deposited essentially at sea level. This rock is composed of quartz grains cemented by syntaxial quartz overgrowths. Rare detrital zircons and potassium feldspar grains are also present. All grains are well rounded and range in size from coarse to fine sand. Thin section data support the interpretation of this unit as having been deposited in high energy conditions, possibly near wave base.

The next several meters of section are not exposed. A complete section from the erosional unconformity at D to the quartzite is exposed in the moat on the southwest side of the fort.

Localities F to I, Orwell Limestone

Locality F At the north entrance to the fort

Beds from here to Locality I are the Orwell Limestone, a poorly and thickly bedded limestone that is mostly lime-mud and lime-silt.

Beds exposed here are also seen in Locality G and again on the lake shore east of Locality H. The white-weathering massive lime-mud at the base (and a bit higher on the vertical face), is the Lowville lithofacies. The Lowville, with vertical tubes *(Phytopsis)*, is commonly interpreted as a tidal flat deposit; alternately, the Lowville may have formed in the zero-energy environment of a lagoon.

This lithology is composed of subequal amounts of carbonate mud, sparry calcite cement, with allochems of algae and intraclasts dominant. Texturally the rock would be termed a packstone. Minor amounts of dolomite and quartz are also present. Intraclasts are composed of micrite in which rare skeletal fragments and dolomite rhombs are found. Based on this texture and composition this rock would be interpreted as having formed in relatively high energy, shallow water conditions (well within the photic zone) where sediment could be reworked and re-deposited.

Just above the Lowville, there is a bed with centimeter-sized clasts - probably storm deposits - similar to a bed near the base of the section at Locality A. Higher on this wall are some black chert nodules. Fossils include *Lambeophyllum* (solitary coral), *Foerstephyllum* (honey-comb coral), and some moderately spired snails.

Locality G Walk north across road; ledges extending north to lake shore. WATCH FOR POISON IVY

Fossils become abundant: *Lambeophyllum*, *Foerstephyllum*, *Stromatocerium*, straight nautiloids. Snails include the high-spired slender *Hormotoma*, and the sharp-shouldered *Lophospira*. One mass of *Foerstephyllum* is nearly a meter across. It and the smaller ones are detached; no reef-like features are recognized. On some bedding surfaces, the black chert is associated with large horizontal burrows.

The highest bed in the set of ledges is a thin black chert that is a centimeter or so thick. Near the lake shore, the chert shows prints of brachiopod shells. The same section from Lowville up is seen on the shore but is hard to study because of glacial abrasion and rounding. Above the continuous black chert bed there is a 1 meter covered interval, represented by beds in the quarry floor at Locality H.

Locality H Quarry, Fletcher Marble Company.

The quarry was worked by the Fletcher Marble Company about 1868 in an unsuccessful attempt to find a "black marble" dimension stone. The quarry is reportedly only a meter or so deep. The narrow spit going north was built to load blocks on barges, but evidently no blocks were shipped.

Quarried blocks show abundant bryozoans, pelmatozoan stems, large brachiopods, and fragments of a large trilobite *(Isotelus?)*. The face below the bench shows vertical burrows, a layer or two of clam shells concave down, and chert masses. Just above the bench, there is a Lowville-like lime-mud overlain by current-bedded lime-silt.

Walk north to the artificial sand beach and then west along the shore.

The upper part of the Orwell is still massive and poorly bedded. It contains fairly abundant opercula (lids) of the snail *Maclurites*, about at the lake shoreline. Faint *Receptaculites* are present, and the overlying beds have *Lambeophyllum*, *Foerstephyllum*, *Stromatocerium*, and a clam *(Ambonychia?)*.

Units sampled within this interval are similar in their characteristics: subequal spar cement and carbonate mud matrix with variable quantities of skeletal fragments. Dolomite and quartz grains are absent. Overall diversity of skeletal grains is higher in these horizons than elsewhere in the stratigraphic sequence. Algae is present, but much less common. Intraclasts are locally the most abundant allochem. These characteristics taken together suggest that these units were deposited in relatively shallow water of moderate energy levels (enough to winnow away some carbonate mud and generate intraclasts).

The Orwell Limestone was evidently deposited in the photic zone, possibly in a lagoon. The Orwell lacks dolostone beds. Only a few thin layers show sorting and current bedding, and the predominant texture is lime-mud, with whole fossils. Several fossils - the corals, *Maclurites*, *Stromatocerium* - suggest the sea bottom was shallow enough to be in the photic zone, perhaps 10 to 30 m deep.

Localities I to K, Glens Falls Limestone

Locality I A beach gravel that covers about 1 m of section

This separates the outcrops of Orwell Limestone and Glens Falls Limestone, which extends to the west shore. **Localities J and K** are beach gravels (covered intervals), like Locality K.

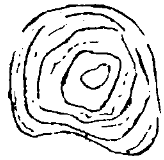
Private Property is in the western part, by Locality K. Do not go on that part of the shore (sample collecting of past years has left sharp edges for swimmers).

The Glens Falls Limestone is thin-bedded, and at least some beds are graded, with coarser particles and fossils in the lower part and lime-mud with scarce fossils in the upper part. Where the upper part is worn off, fossils show. These include abundant black fragments of trilobites (especially glabella of *Flexicalymene*), common *Sowerbyella* (small smooth-shelled wide-hinged brachiopod), and other brachiopods. There are occasional slender pelmatozoan stems and also slender stick bryozoans.

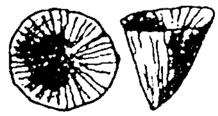
These rocks appear much finer-grained in the outcrop and in thin section. Point count data indicates that these horizons are dominantly composed of carbonate mud with variable amounts of skeletal grains present. Spar cement is present within recrystallized grains, as shelter fabric, and less frequently as interparticle cement. Skeletal fragments of brachiopods, bryozoa and trilobites reach their maxima in these horizons. Algae have not been recognized. Texturally these rocks would be termed wackestones. The overall fine grain size, diversity of skeletal fragments and absence of algae suggests that these rocks were deposited at depths near or below the photic zone and in generally quiet water conditions.

Algae
Girvanella (x 1) "cocktail-onion";
concentric layering, small, abundant.

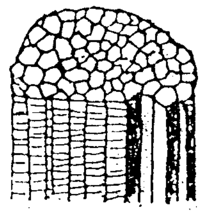
Stromatoporoid
Stromatocerium rugosum (x 1/10)
irregular, sub-concentric masses to 30 cm across
(looks as though a cow just went by)



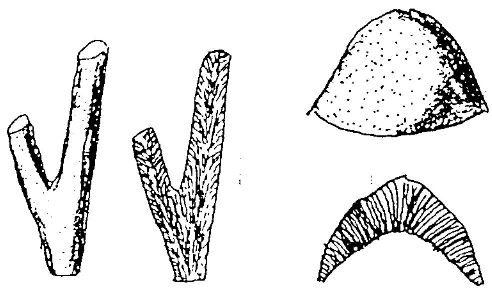
Corals (Coelenterates)
Lambeophyllum profundum (x 1)
oldest genus of solitary coral in geologic
record; shaped like ice-cream cone; presumably
lived in shallow photic zone with algae.



Foerstephyllum wissleri (x 1)
honeycomb variety of colonial coral; presumably lived
in shallow photic zone with algae; this species named
after Professor Benjamin Wissler, Middlebury College.
Sketch shows top (honeycomb) and side (columns;
cut-away columns with interior tabulae).



Bryozoans (x 2, x 1)
Colonial coral-like animals with microscopic
tubes for each individual; surface has tiny
pin-hole apertures, visible with hand lens;
interior has hair-like fibers. Bryozoans are
filter feeders, needing clear water.



(shape and cross-section) "stick" Prasopora

Brachipods (2 shells) (x 1, 1/2)
Varieties are wide or narrow-hinged, smooth or
marked with radiating lines or ribs; some show
concentric growth lines. Diverse assemblage of
brachiopods indicates open marine conditions.

a. Sowerbyella; b. orthid; c. rhynchonellid

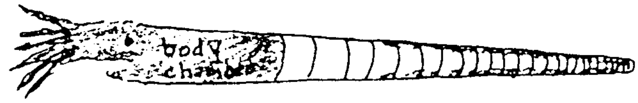
a.

b.

c.

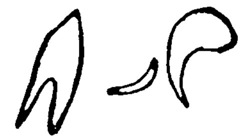
FIGURE 5A. Fossils of the Crown Point, New York, Section.

Nautiloids (x 1/5, 1/10)
Belong to Mollusca, Cephalopoda. Related to squids; swimmers, predators. Chambers behind body chamber are preserved.

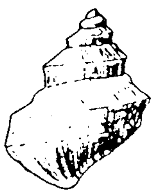


Gastropods (Mollusca; snails)
Maclurites is flat-coiled; probably grazed on algae in very shallow water. Its operculum is a thick-walled "hand"-shaped lid. Many snails have moderate to high spires (coils).

x 1/5
Maclurites



x 1/3
opercula

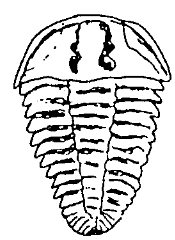


x 1
Lophospira

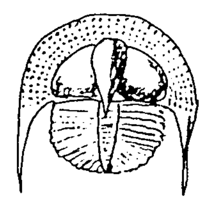
x 1
Hormotoma

x 1/2
Lecanospira

Trilobites (x 1)
Belong to Arthropoda. Like locusts, they molted, so one animal could leave many exoskeleton fragments. The cephalon (head region) is most important part for identification.



Flexicalymene



Cryptolithus

Pelmatozoans (x 1/2)
Belong to Echinodermata. Pelmatozoan stem (of crinoid, cystoid, etc.) comes apart in the sediment, leaving disks with round or star-shaped holes; cup with the living chamber seldom found here. Echinoderms live only in water of normal salinity.

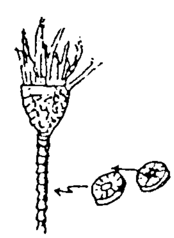


FIGURE 5B. Fossils of the Crown Point, New York, Section.

APPENDIX B

TABLE. 1

Constitutient Composition Analysis
of Crown Point Section, New York
Using Point Count Method

Horizon (meters)	Spar cement	Micrite matrix	Dolomite	Quartz/ terrigenous mud	Pelmatozoans	Echinoderms	Brachiopods	Trilobites	Algae	Bryozoans	Gastropods	Intraclasts	Unidentified skeletal fragments
116	51	16				2	3	3		17			7
105		72					6	2					13
103	19	54		3	10			8					13
95	22	36				3	1		1	1	1	32	2
93	21	48			7			2	3			4	1
85	18	30	5	2					26			14	4
75				100									
66	18	18	30	5					27				
54	47	6				1			23			20	
45			83	17									
24	57	15		11					12			1	
4.8	21	25	11	14	4	3	2		17				1

Data shown in relative percentages.
Percentages rounded off to the nearest whole number.
Point count based on 200 grains per slide.

August 24, 1985

THE CAMBRIAN PLATFORM IN NORTHWESTERN VERMONT

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VERMONT GEOLOGY
VOLUME 4

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ABSTRACT

A review of the sedimentology of the formations which comprise the Cambrian platform sequence in northwestern Vermont is presented. The sedimentology and depositional environments of the Lower Cambrian Cheshire Quartzite, Dunham Dolomite, and Monkton Quartzite and Upper Cambrian Danby Quartzite have been studied in detail and preliminary observations have been made of the Middle Cambrian Winooski Dolomite. Of these units, all but the Cheshire Quartzite appear to record Peritidal to Shallow Subtidal and Platform Margin sedimentary facies. The characteristics of each facies are summarized and interpretations of depositional environments presented.

As the initial carbonate unit deposited on the newly formed shelf margin, the Dunham Dolomite is important because it records the development of the carbonate platform and establishment of the platform geometry preserved in subsequent units. Evidence is presented which suggests that a stable platform margin was established in mid to late Dunham time and all subsequent platform margin deposits are found localized in the same paleogeographic position on the shelf.

The Cambrian sequence can be characterized as consisting of alternating siliciclastic and carbonate deposits. This stratigraphic sequence is thought to be the result of variations in sediment supply and distribution, and not due to variations in eustatic sea level. Platform Margin deposits, which are sensitive indicators of eustatic sea level changes, are not extensive enough to suggest that eustatic sea level changes occurred frequently.

INTRODUCTION

Cambrian to Lower Ordovician clastic and carbonate sediments in the Vermont portion of the northern Appalachians were deposited on a tectonically stable shelf following late Precambrian rifting of the Iapetus Ocean (Rodgers, 1968). The shallow-water platform bordering this young ocean basin was affected by tides and wind-generated currents. These pericontinental seas passed seaward offshore into open-shelf regions and ultimately into deeper water basins (Mazzullo and Friedman, 1975). Very generalized facies sequences have been summarized for platforms which exhibit this geometry, including those of the Cambrian and Lower Ordovician of the Appalachians (Rodgers, 1968; Palmer, 1971). The facies associated with the pericratonic portion of this sequence in the Appalachians have been described in detail by Myrow (1982), Gregory (1982), Rahmanian (1981), Chisick and Friedman (1982), Braun and Friedman (1969), and Markello and Read (1981). Pfeil and Read (1980) and Reinhardt (1977) have described the facies characteristic of the platform margin and basin environments. Few of these works document the complete sequence from epicontinental seas through to Platform Margin and Basin environments. The Vermont portion of the northern Appalachians provides a unique opportunity to develop a model for the nature of Cambrian to Lower Ordovician sedimentation in complete stratigraphic sequences which range from tidally-influenced through Platform Margin and Basin deposits.

It should be stressed that the shallow water platforms bordering the Iapetus Ocean were developed on continental crust. The actual continental/oceanic crust transition, represented by the continental shelf/slope transition, lay much further to the east (Rodgers, 1968). The platform/platform margin facies changes described herein represent significant bathymetric changes developed wholly on continental crust, and are related to graben structures on the rift margin.

This paper summarizes our present state of knowledge with regard to the sedimentary facies and evolution of Cambrian to Lower Ordovician deposits on the portion of the continental margin of the Iapetus Ocean presently exposed in northwestern Vermont.

GEOLOGIC SETTING AND STRATIGRAPHY

The Cambrian to Lower Ordovician stratigraphic sequence in western Vermont crop out in a north-south trending belt (Fig. 1), a region bordered on the east by the Green Mountain anticlinorium, a belt of Precambrian rocks thought to represent the easternmost occurrence of the North American craton in the Lower Paleozoic (Rodgers, 1968). The north-south trending outcrop belt consists of several major fold belts (St. Albans synclinorium, Middlebury synclinorium) and trust sheets (Champlain, Hinesburg, Highgate Springs, Pinnacle thrusts). The northwestern portion of this outcrop belt is ideally suited for sedimentologic studies of the Cambrian to Lower Ordovician stratigraphic sequence because its protected position within the Quebec Reentrant (Williams, 1978; Thomas, 1978) kept deformation and metamorphism associated with the Taconic and Acadian orogenies to a minimum. The most complete exposures of the Lower Paleozoic are contained within thrust sheets in this region. Stratigraphy within these thrust sheets is coherent and, with the exception of pressure solution and stylolitization, is relatively undeformed. Deformation is most severe near thrust contacts (Dorsey and others, 1983).

Cambrian and Lower Ordovician clastics and carbonates in the northern Appalachians were deposited on a tectonically stable shelf which developed following late Precambrian rifting of the Iapetus Ocean. This shelf was undergoing thermal subsidence throughout the interval when Cambrian and Lower Ordovician sediments were being deposited. Thermal subsidence models have not yet been developed for the northernmost portion of the Vermont Appalachians, however the subsidence history of the Cambrian margin in the Taconic region has been described by Baldwin (1980, 1982). Based on the generalized thermal subsidence models of other Cambrian margins by Bond and Kominz (1984), we can infer that thermal subsidence values were initially very high in the latest Eocambrian and earliest Lower Cambrian and subsequently decreased throughout the Cambrian as the young rifted margin progressively cooled. Further work on the thermal subsidence history of the northwestern Vermont portion of the northern Appalachians will be necessary before comparisons of stratigraphic sequences can be made to other regions bordering the Iapetus Ocean. These theoretical models do help us understand what factors may have influenced sedimentation patterns on the Cambrian platform. For example, they may help us to ultimately understand the origin of the alternating siliciclastic and carbonate sedimentation which characterizes the Cambrian sequence in Vermont. Rowley (1979) has suggested that eustatic sea level changes have been responsible for deposition of the Cambrian siliciclastic units of the Cheshire, Monkton and Danby formations. Evidence will be presented later which suggests that, at least in northwestern Vermont, major eustatic sea level changes were not responsible for generating the Cambrian stratigraphic sequence.

STRATIGRAPHIC TERMINOLOGY

The Cambrian through Lower Ordovician stratigraphic sequence in northwestern Vermont was divided into two sequences by Dorsey and others (1983): a western shelf and an eastern basinal sequence (Fig. 2). The western shelf sequence is composed of alternating siliciclastic (Cheshire, Monkton, Danby formations) and carbonate (Dunham, Winooski, Clarendon Springs formations) units. Prior to the stratigraphic sequence of Cady (1945), the stratigraphic nomenclature for the rocks comprising the western shelf sequence was quite complex. Reviewing first the carbonate units, Keith (1923, 1932) and Schuchert (1937) considered all the dolomites in northwestern Vermont to be equivalent to the Lower to Middle Cambrian Monkton Quartzite and termed these beds the Winooski Dolomite. A similar sequence of dolomite in the Oak Hill Succesion in adjacent southern Quebec was termed the Dunham Dolomite by Clark (1934). Cady (1945) recognized that two different dolomites were present in northern Vermont and termed the lower, older the Dunham Dolomite and retaining the name Winooski for the younger. The stratigraphic nomenclature of the final carbonate unit, the Clarendon Springs Formation, is also quite complex. Keith (1923) originally recognized a structureless dolomite unit which overlay the Dunham Dolomite and Parker Slate in the Milton region, and which he termed the Milton Dolomite. Subsequent dating of the shales associated with the Milton Dolomite (Schuchert, 1937) revealed that it was in fact, uppermost Cambrian in age. This led Cady (1945) to extend the name Clarendon Springs Dolomite to the dolomite horizons in the Milton area. The Clarendon Springs had first been described by Keith (1932) from west-central Vermont, to describe a dolomite horizon below the Shelburne Marble. Subsequent evaluations of the age of the Clarendon Springs Formation have resulted in a reassignment of its age as lowermost Ordovician.

As for the siliciclastic units, the Cheshire Quartzite was named at its type locality in Cheshire, Massachusetts by Emerson (1917). A basal Cambrian siliciclastic rock unit was recognized within the Oak Hill Succession in Quebec and termed the Gilman Quartzite (Clark, 1934). Within Vermont, a unit equivalent to the pure quartz arenite of the Cheshire Formation in Massachusetts and the argillaceous sandstone of Quebec was recognized by Keith (1923) and Cady (1945) and was termed the Cheshire Quartzite. As mentioned above, the Monkton Quartzite was recognized at an early date (Keith, 1923) as a siliciclastic unit which lay between two carbonate formations. The Danby Quartzite was also described by Keith (1923), who distinguished the siliciclastic-rich portion of this unit from the carbonate-rich horizons, termed the Wallingford Formation. Cady (1945) grouped these two formations together and recognized a lower siliciclastic unit and the upper Wallingford (carbonate) unit.

The stratigraphic terminology for the Cambrian to Lower Ordovician of northwestern Vermont summarized here extends into southwestern Vermont as well. It should be noted however, that sedimentation continued through the Lower Ordovician (Beekmantown Group) in southwestern Vermont. The stratigraphy and depositional environments represented by Beekmantown Group rocks is summarized in Braun and Friedman (1969), Mazzullo and Friedman (1975) and Mazzullo (1978).

The stratigraphy of the basinal sequence which corresponds to the shelf sequence just described, but representing sediments deposited in deeper water to the east, consists of shale units (Parker and Skeels Corner slates) with isolated carbonate breccia units (Rugg Brook, Rockledge, Mills River conglomerates). Unlike the western shelf sequence, correlations within the eastern basinal sequence are well developed (Fig. 2). The stratigraphic nomenclature for these units was developed by Shaw (1954, 1955) based on field mapping and faunal zonations. Two important revisions of Shaw's correlations have been made. The first of these is the work of Palmer and James (1980) in which a hiatus in sedimentation within the Parker Slate was recognized. The second revision was made by Dorsey and others (1983). On the basis of field relationships they recognized that the Skeels Corners Slate was a diachronous unit, gradationally and conformably overlying both the Lower Cambrian Dunham Dolomite and Lower Ordovician Clarendon Springs Formation.

DEPOSITIONAL ENVIRONMENTS OF THE WESTERN SHELF SEQUENCE

At this time the sedimentology and environments of deposition of the Cheshire Quartzite, Dunham Dolomite, Monkton Quartzite and Danby Quartzite have been studied, with results presented in unpublished Masters' Theses at the University of Vermont and in several Geological Society of America abstracts. In addition, there have been other works which have addressed regional aspects of these rocks (Mehrtens and others, 1983; Dorsey and others, 1983). The remainder of this paper will review the major findings of these works and present an interpretation for the evolution of the Cambrian shelf in western Vermont. It has been proposed (Mehrtens and Gregory, in review) that the geometry of the shelf in the Lower Cambrian developed during deposition of the Dunham Dolomite was maintained throughout the remainder of the Cambrian.

PRE-CHESHIRE UNITS

The Pinnacle and Fairfield Pond formations underly the Cheshire Quartzite in central Vermont. The stratigraphy and structure of these units was studied by Tauvers (1982) and their depo-tectonic

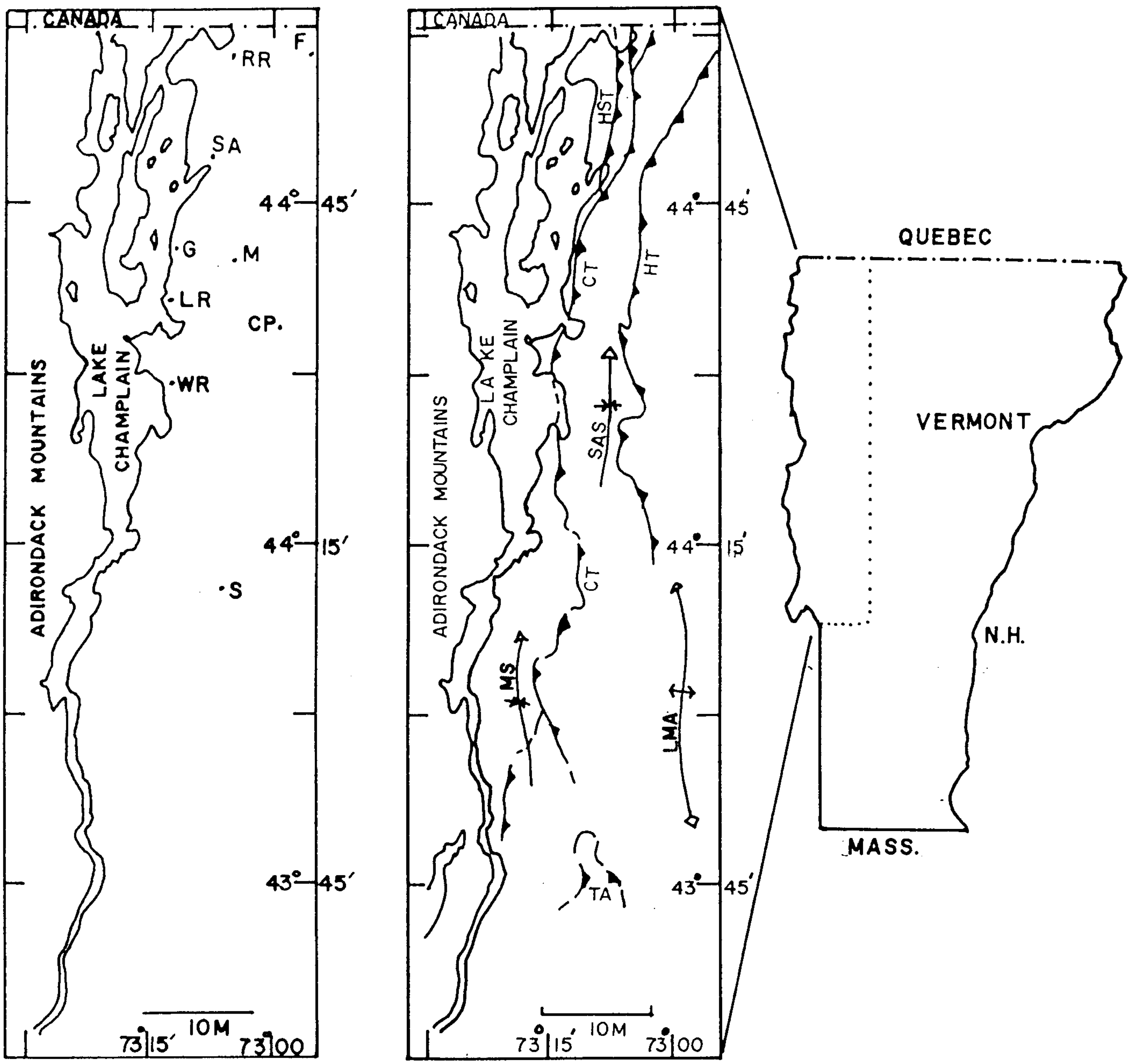


Figure 1. Locality maps of the study area showing the major structural features of northwestern Vermont (right) and the locations of measured stratigraphic sections of the Cambrian: TA=Taconic allochthon; LMA=Lincoln Mountain anticlinorium; MS=Middlebury synclinorium; SAS=St. Albans synclinorium; CT=Champlain thrust; HT=Hinesburg thrust; HST=Highgate Springs thrust; B=Bristol; S=Starksboro; WR=Winooski River; SH=Shoreham; MF=Munson Flats; CP=Colchester Pond; M=Milton; LR=Lamoille River; G=Georgia; SA=St. Albans; RR=Rock River; F=Franklin; H=Hinesburg.

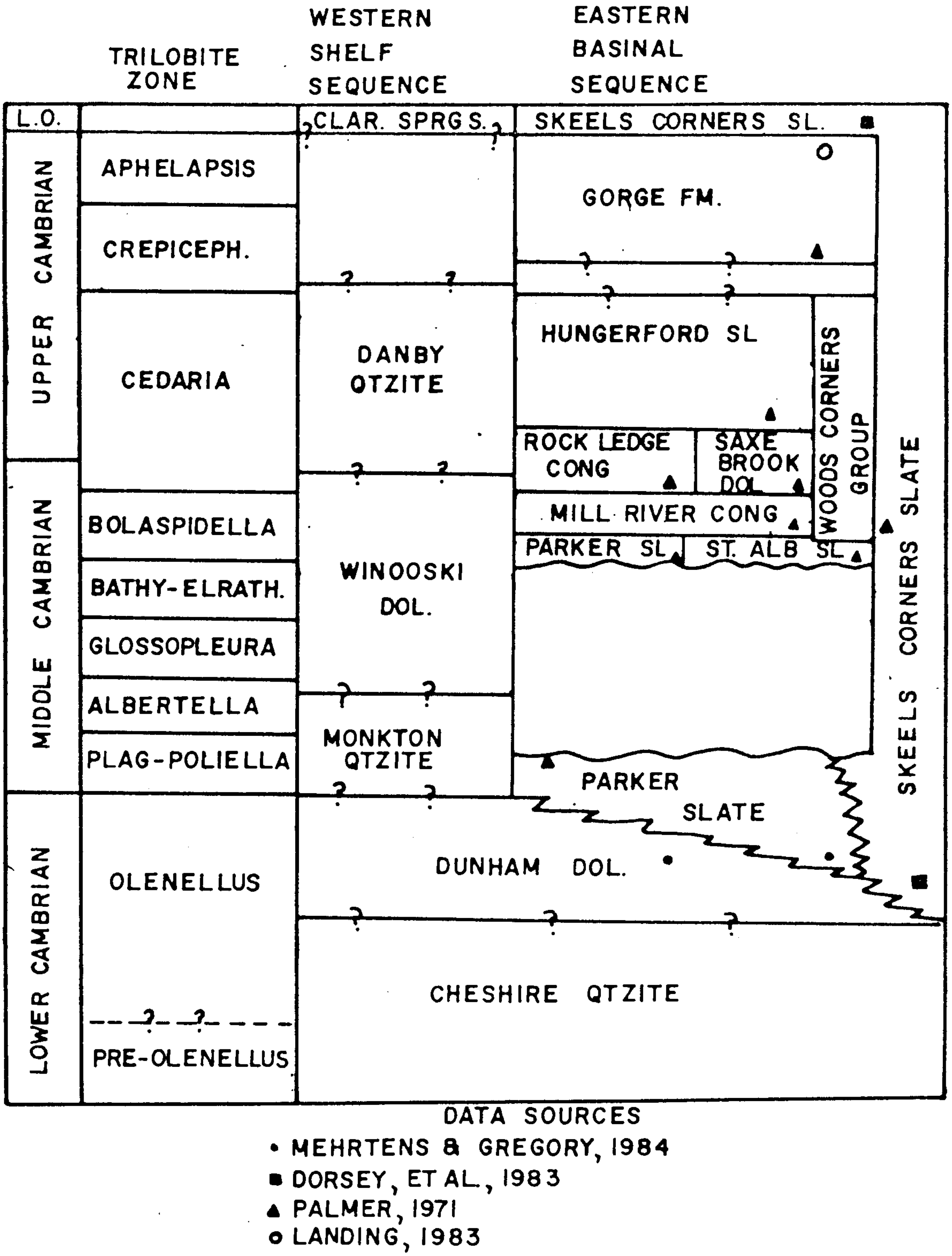


Figure 2. Correlation chart for the shelf sequence, exposed in the westernmost portion of Vermont, and the basinal sequence, an eastern equivalent. The Cambrian sequence consists of alternating siliciclastic and carbonate units. The basinal equivalent of the Cheshire Quartzite has not been identified.

setting described by Dorsey and others (1983). The Pinnacle and Fairfield Pond formations are interpreted as representing rift basin fill sediments deposited following initial rifting in the Eocambrian. Doolan and others (1982) has suggested that this rifting may have occurred at approximately 560 my before present. The topography of the rift basin resulted in a basal unit of coarse clastics, possibly alluvial fan in origin (Tauvers, 1982) overlain by finer-grained siliciclastic sediments of the Fairfield Pond Formation, interpreted as forming in marginal marine basins. The contact of the Fairfield Pond Formation with the overlying Cheshire Quartzite was shown by Tauvers as being conformable in nature.

CHESHIRE QUARTZITE

A detailed field and petrographic study of the lithofacies of the Cheshire Quartzite in central Vermont was completed by Myrow (1982, 1983). The description presented here is based on his work. The Cheshire Quartzite is an important unit because it represents the transition from the siliciclastic rift basin fill sediments of the Pinnacle and Fairfield Pond formations to sedimentation on a stable carbonate platform (Dunham Dolomite).

Myrow recognized ten distinct lithofacies within the Cheshire Quartzite (Fig. 3). These lithofacies were recognized on the basis of composition, sedimentary structures, bedding styles, and biogenic structures. The lower unit of the Cheshire Quartzite is arkosic to subarkosic in composition; it is similar to the Gilman Quartzite that is exposed in nearby southern Quebec. The upper unit of the Cheshire is a quartz arenite and is similar to the Cheshire at its type section in Massachusetts.

The lower Cheshire is comprised of five lithofacies: 1) fine-grained, mottled grey, argillaceous arkose. Distinctive characteristics include extensive bioturbation; thin, white, rippled beds and disseminated shale partings. A strong penetrative schistosity has often made recognition of the ripples difficult. 2) fine-grained, white subarkosic and fine-grained grey arkosic beds. Clay drapes commonly overlie the subarkosic horizons. Distinctive features of this lithofacies includes ripple bedding, wavy and lenticular bedding, thick and thinly interlayered bedding (Reineck and Singh, 1973), horizontally stratified and cross laminated beds, and U-shaped vertical burrowing. 3) fine-grained white subarkosic beds with thin clay drapes. Distinctive characteristics of this lithofacies include: medium to thick massive and horizontally stratified beds, occasionally exibiting tabular cross stratification, massive lenticular beds, lenticular low angle trough cross-stratified beds, rippled beds, reactivation surfaces and erosional surfaces. 4) thin, lenticular, structureless sand bodies with erosional bases and flat upper surfaces. Low angle cross stratification can be present. 5) tabular sand beds characterized by planar, non-erosive bases and reworked tops, and a notable lack of internal structures.

The upper Cheshire is composed of three lithofacies: 1) A pink to white weathering, moderately to poorly sorted, massive, structureless, fine-grained quartzite whose composition ranges from quartz arenite to arkose. Minor amounts of carbonate cement can be present. 2) A shale clast conglomerate composed of interbedded quartzite with shale clasts or chips. 3) Massive quartzite beds, lenticular in shape with large scale erosional surfaces at their bases. Beds exibit large scale trough cross stratification.

INTERPRETATIONS

These eight lithofacies can be interpreted as representing sediments deposited on a newly formed shelf, at least in part within wave base. The Cheshire Quartzite is thought to represent the marine shelf sand deposited over the underlying irregular rift basin topography. This interpretation is based on: 1) position within the Cambrian stratigrapic sequence; 2) absence of any lithofacies characteristics of the supratidal environment; 3) comparison to stratigraphic sequences of similar rock units. This interpretation differs from that originally presented by Myrow (1982, 1983), who originally suggested that the Cheshire Formation represented a transgressive sequence of tidal flat to shallow subtidal sediments. Myrow's interpretation was reevaluated as a result of recent literature describing the association of rippled sand and clay drapes characteristic of the lower Cheshire as probably resulting from storm sedimentation on open shelves (see Nelson, 1982; Einsele and Seilacher, 1983, for example). This reinterpretation would also explain: 1) the absence of any evidence of the supratidal at the base of the lower Cheshire, and 2) the gradational upper contact of the Cheshire Formation with the Peritidal Facies of the overlying Dunham Dolomite. For these reasons it now appears that the Cheshire can be interpreted as representing shelf sedimentation (lower Cheshire) exhibiting periodic storm sedimentation, capped by prograding strandline sands (upper Cheshire).

DUNHAM DOLOMITE

The lithofacies and depositional environments of the Dunham Dolomite were studied by Gregory (1982) and Mehrtens and Gregory (in review). These authors recognized that the Dunham Dolomite was composed of four major lithofacies representing the Peritidal, Subtidal/Open Shelf, Channel and Platform Margin environments, which formed a transgressive sequence from the Peritidal to Platform Margin (Fig. 4). The Dunham Dolomite serves as a model for sedimentation on the carbonate platform throughout the remainder of the Cambrian. The base of the Dunham Dolomite is in gradational and conformable contact with the underlying Cheshire Quartzite and the uppermost Dunham Dolomite grades into the basinal Parker and Skeels Corners slates.

The Peritidal Facies of the Dunham Dolomite is characterised by a bedding style termed "sedimentary boudinage" which describes the rhythmic interbedding of lithologies and subsequent differential compaction to produce beds which exhibit pinch and swell, or boudinage. In the Dunham Dolomite the interlayering consists of beds of pure dolomite (white) and silt-rich dolomite (pink). These two lithologies are frequently disrupted by bioturbation which mottles textures. Some horizons exhibit poorly developed imbricated intraclasts of the pure white dolomite in the red silt-rich dolomite. The silt-rich dolomite frequently exhibits cryptalgalaminite textures.

The Subtidal/Open Shelf Facies is characterized by shallowing-up cycles up to 10 meters thick which have at their base massive beds of dolomite with quartz sand disseminated throughout (Fig. 5). Beds have a mottled appearance due to the abundance of bioturbation. Overlying this lithology is a package of the rhythmically interbedded dolomite and silt-rich dolomite of the Peritidal Facies. These shallowing-up cycles are interpreted to represent sediments which have prograded into the adjacent subtidal shelf. Both the Peritidal and Subtidal/Open Shelf Facies are in-

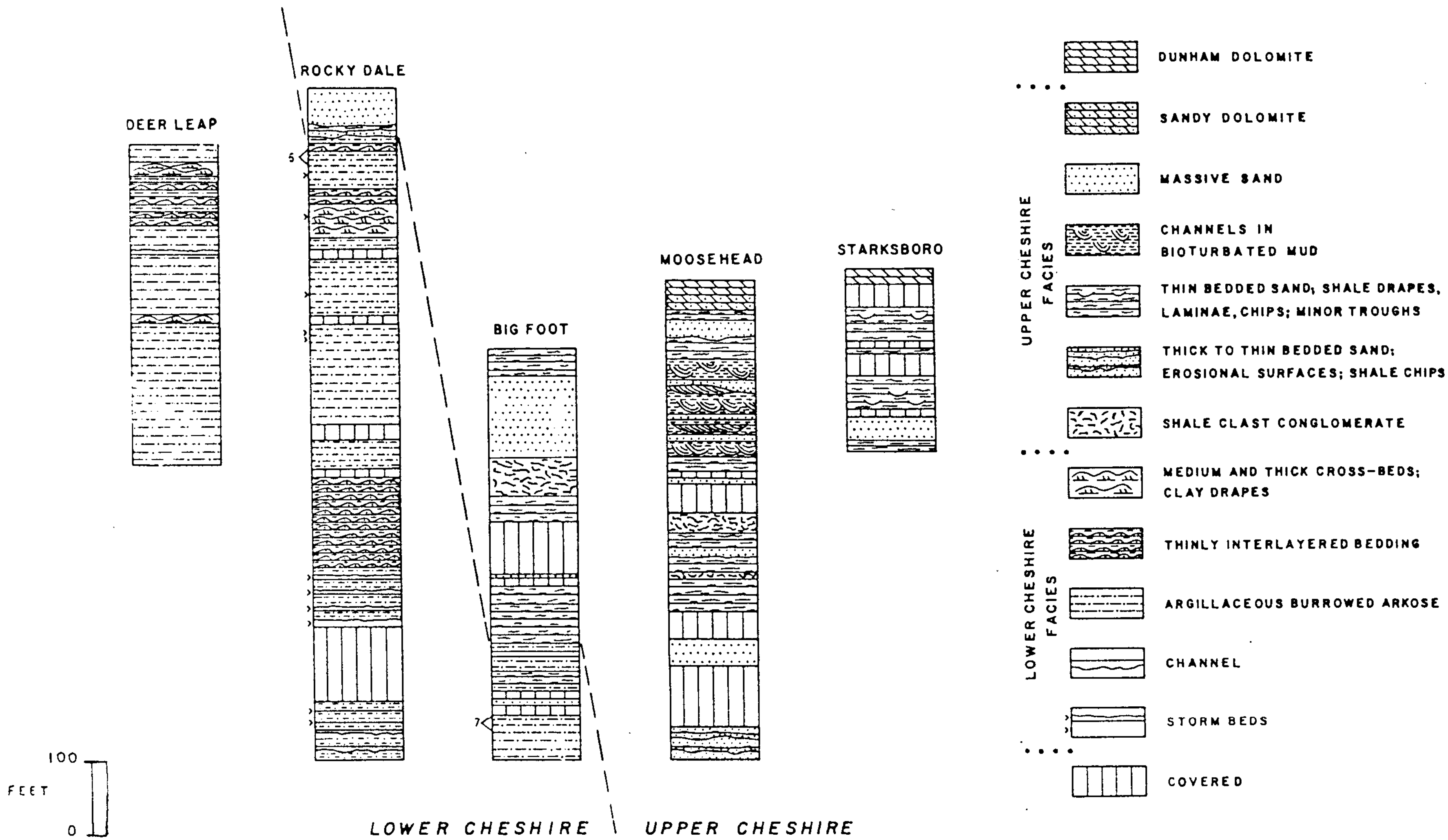


Figure 3. Stratigraphic columns of the Cheshire Quartzite from Myrow (1982, 1983). Shown is the distribution of the 11 lithofacies recognized by Myrow. These were subsequently grouped into the eight lithofacies discussed in the text.

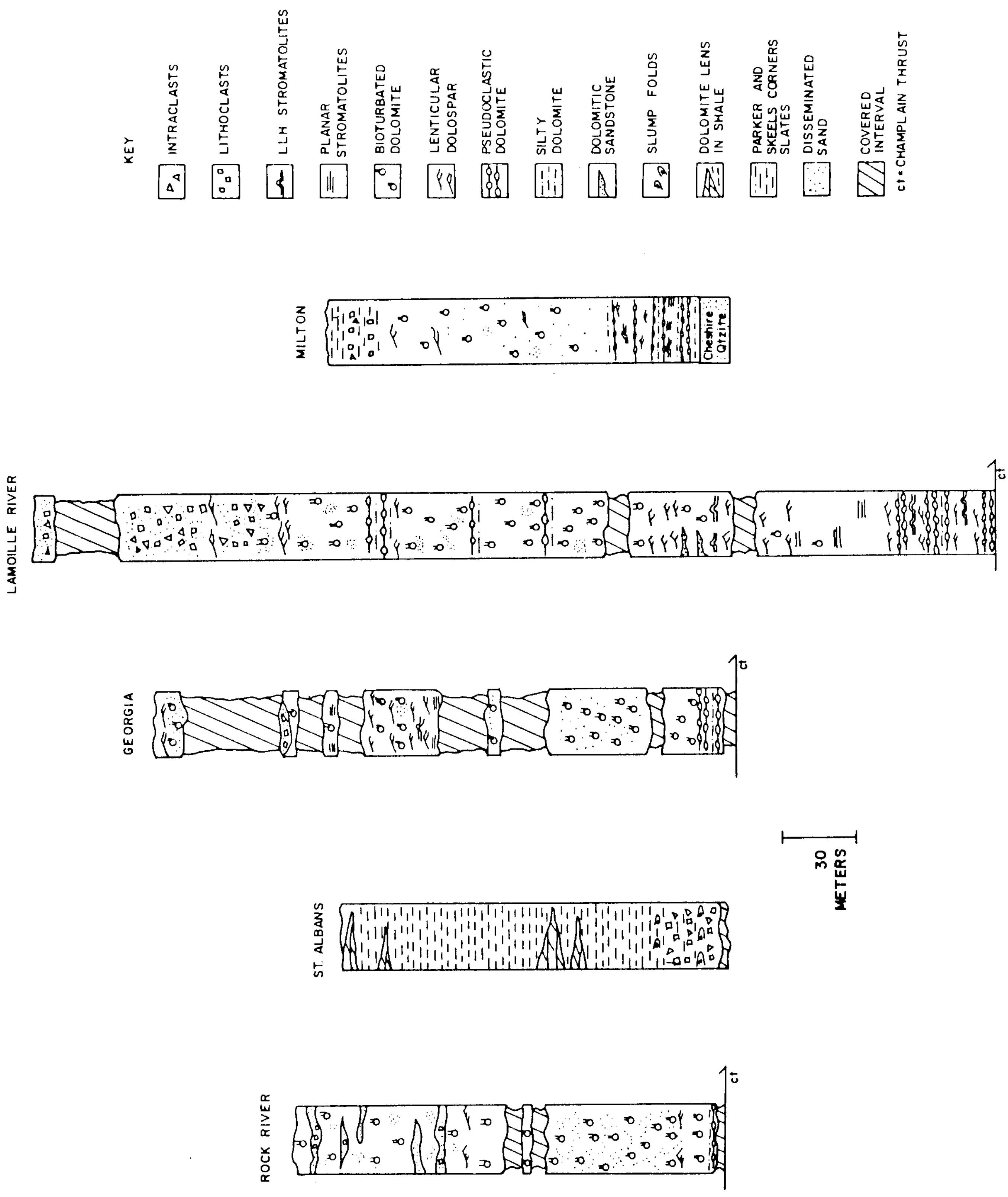


Figure 4. Stratigraphic columns of the five thickest outcrops of the Dunham Dolomite. A sixth thick section from the subsurface near Franklin is not shown. The exposure at Milton is the only complete exposure of the Dunham Dolomite: the gradational contacts with the underlying Cheshire Quartzite and the overlying Skeels Corners are both exposed. Elsewhere the base of the Dunham Dolomite is truncated by the Champlain thrust.

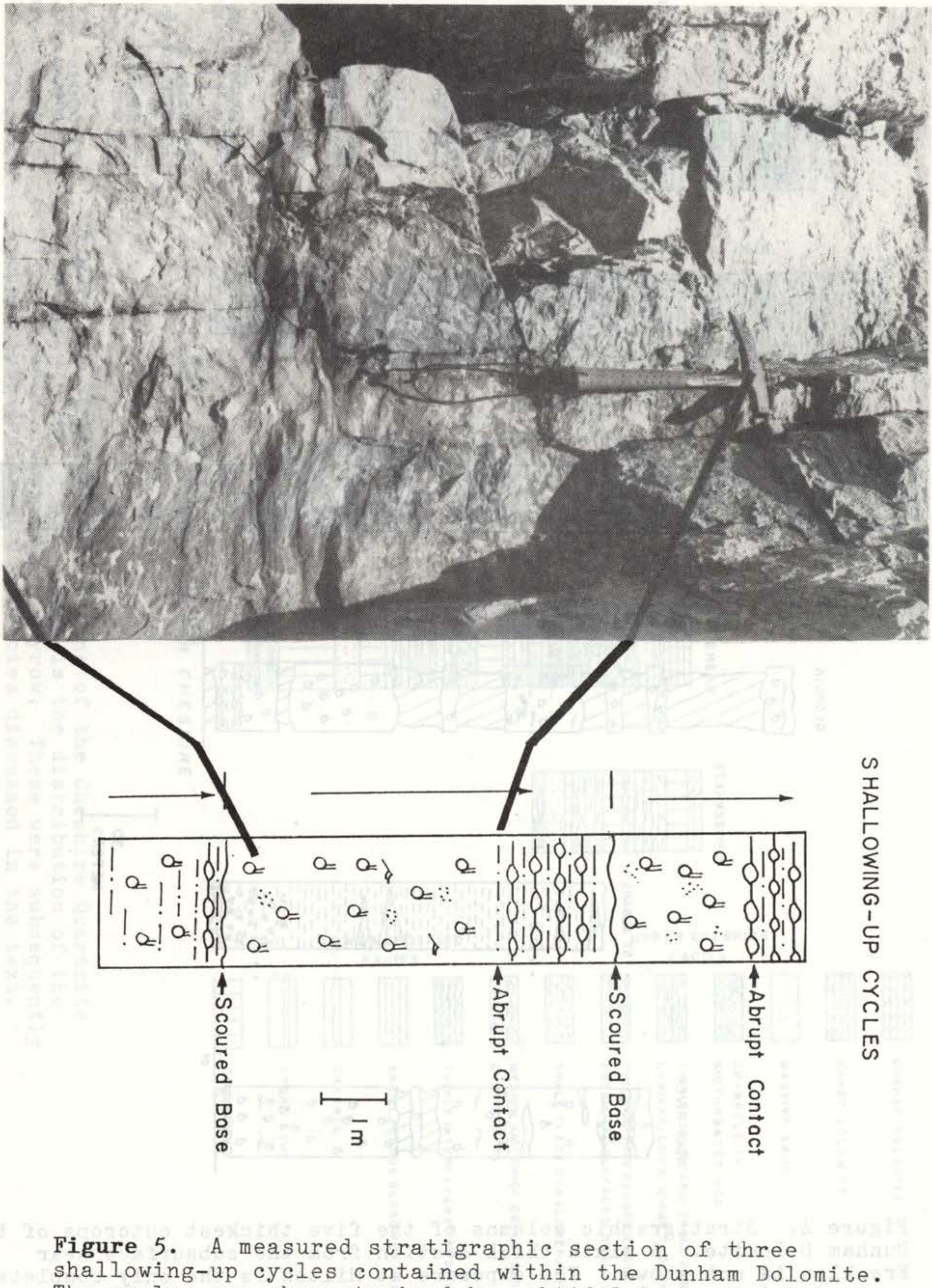


Figure 5. A measured stratigraphic section of three shallowing-up cycles contained within the Dunham Dolomite. The cycles are characterized by subtidal bases overlain by peritidal caps. See Figure 4 for symbols.

terbedded with rocks characteristic of the Channel Facies. These deposits exhibit lenticular beds with downcutting basal contacts. They contain quartz sand and both intraformational and exotic clasts. Trough cross stratification is common within channels.

Rocks characteristic of the Platform Margin Facies exhibit polymictic breccias within subaqueous debris flows and thick graded dolomitic sandstone beds interpreted as turbidites. This facies grades basinward into the Parker and Skeels Corner slates.

Analysis of the distribution of the Platform Margin lithofacies is important in developing a model for the geometry of the Lower Cambrian carbonate platform. The distribution of the platform margin and basin transition can be used to determine the position of the edge of the Dunham platform. Analysis of the distribution of facies and isopach maps for the Peritidal, Subtidal/Open Shelf and Platform Margin Facies indicates that significant facies changes occur both parallel (north-south) and perpendicular to depositional strike (west-east) (Fig. 6). The down-dip facies change to the east is related to passage into the adjacent deeper water sediments of the Iapetus Ocean. The north-south facies change is related to the existence of a reentrant within the Dunham shelf, termed the St. Albans Reentrant, a foundered graben within the shelf. The existence of this reentrant was first noted by Shaw (1958, Franklin Basin) who described the interstratified shale and conglomerate horizons in this region (Fig. 2). Stratigraphic relationships of these rocks, especially those of the Parker and Skeels Corners slates, were refined by Palmer (1971) and Dorsey and others (1983). Based on: 1) thinning the shelf facies and thickening of the platform margin facies; and 2) outcrop patterns of the Parker Slate, the St. Albans Reentrant is thought to have been an intrashelf basin which was a major factor influencing the distribution of Dunham and post-Dunham facies. Figure 6 summarizes the proposed geometry of the Dunham platform. The distribution of pre-Dunham facies is from Dorsey and others (1983). The Dunham facies are illustrated, with the Peritidal Facies shown onlapping the Cheshire Quartzite. Basinward of this the Subtidal/Open Shelf, Channel and Platform Margin Facies are shown. This diagram illustrates the postion of the St. Albans Reentrant with the lateral facies transition from the Dunham Dolomite into the Parker Slate. Also shown is the Dunham Platform Margin Facies and its gradational contact with the Skeels Corners Slate. Note that the west to east transition from the shelf to basin occurs on terrane floored by continental crust, as the easternmost limit of the Precambrian basement lay to the east (Doll and others, 1961). The basins in which the Parker and Skeels Corners slates were deposited probably represent a foundered portion of the rifted continental margin. Work by Dorsey and others (1983) demonstrates that this foundering continued following deposition of the Dunham as no shelf units younger than Dunham are found in this region. The facies changes which are present to both the east and north are abrupt and localized. The Cambrian carbonate platform did not build out; rather, upward growth of the platform kept pace with thermal subsidence. Eustatic sea level change is not thought to be a significant factor during Dunham deposition as no significant lateral migrations of facies occurred, and no large-scale Platform Margin deposits are present in the adjacent basin. The Platform Margin Facies for the Dunham and subsequent units occur overlying one another: no progradation into the adjacent basin is observed. This also suggests that eustatic sea level change was not a factor controlling deposition of subsequent units as well.

On the platform to the south and west the Dunham Dolomite is overlain by the Monkton Quartzite. The contact is abrupt but gradational in that the uppermost beds of the Dunham Dolomite consist of shallow subtidal muds with disseminated floating quartz sand throughout, and the basal beds of the Monkton Quartzite consist of interbedded rippled sand and dolomite of the Inter- and Supratidal environments. It is important to note that the environments represented across the contact are similar, and that the primary difference between the two units lies in the relative importance of siliciclastic sand and dolomite. No significant unconformity exists at the contact.

MONKTON QUARTZITE

The lithofacies and environments of deposition of the Monkton Quartzite were studied and summarized by Rahmanian (1981a, b). Ramanian recognized seven lithofacies, three of which consist of mixed siliciclastic and carbonate sediments, three of which are pure siliciclastic deposits and one is an oolitic dolomite facies. The 300 meter thick Monkton Quartzite is composed of cyclic shallowing-up cycles characterized by repetitive packages of: 1) basal subtidal siliciclastic sand shoals and channels overlain by 2) interbedded siliciclastic sand silt and carbonate intertidal flat sediments, capped by 3) carbonate muds of the high intertidal and supratidal flat. These cycles are interpreted to represent prograding tidal flat deposits. Two siliciclastic lithofacies have been recognized: 1) sand bars and tidal channels and 2) mixed rippled sands with mud drapes of the intertidal. These supra-, inter- and shallow subtidal sediments pass downdip to the east and north (into the St. Albans Reentrant) into subtidal oolitic dolomites and platform margin breccias. The Monkton Quartzite, then, exhibits the same distribution of lithofacies as the Dunham Dolomite.

The Monkton Quartzite is also similar to the Dunham Dolomite in the nature of the platform margin-basin transition. The Monkton passes laterally into the Parker and Skeels Corners slates to both the east and north (Fig. 8).

The high degree of similarity between the environments of deposition and facies distribution between the Dunham Dolomite and the Monkton Quartzite suggests that the morphology of the Cambrian platform was established in Dunham time and maintained through Monkton deposition. Although the composition of the platform sediments changed from dominantly carbonate to mixed siliciclastic/carbonate, the environments of deposition in which these sediments were deposited, and the distribution of these environments, are the same. Whatever generated the source for the Monkton sands did not affect the geometry of the platform on which they were deposited. An analogous situation may be seen today in Belize, where south of the carbonate platform fluvial systems deposited siliciclastic sediment on the same shelf, with a zone of mixing between. A higher uplift rate in the source area increases siliciclastic sedimentation, which would be manifested in geologic record by a gradational contact with the underlying carbonate sediment.

The Monkton Quartzite is overlain on the shelf by the Winooski Dolomite. This contact is exposed in a quarry on Route 7 in Winooski. A measured section across the contact is shown in Figure 7. This contact is very gradational: the rippled, shale-draped sands of the Intertidal Lithofacies of the Monkton Quartzite are interbedded with rippled silt-rich dolomites of the Win-

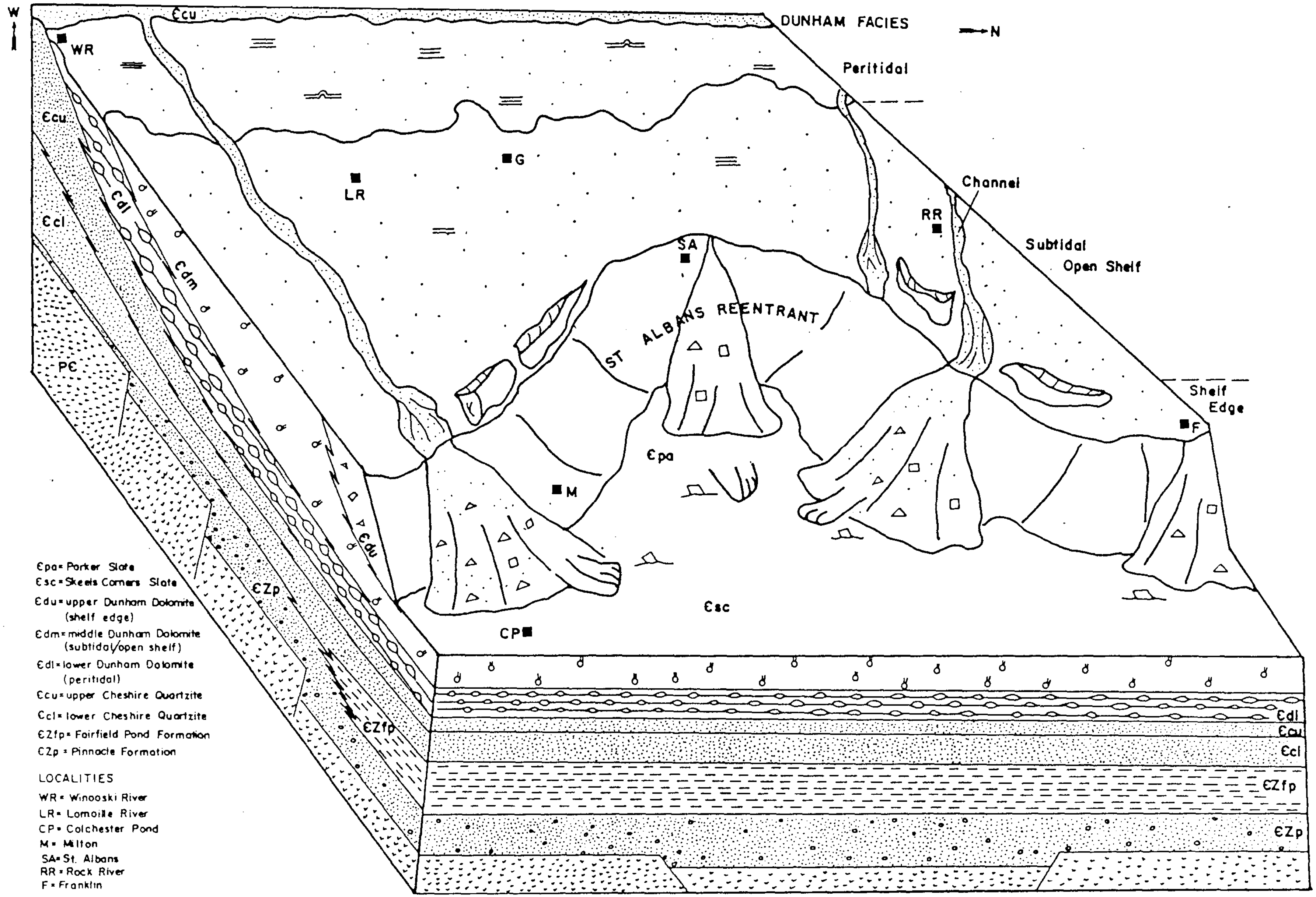


Figure 6. Block diagram summarizing the depositional model proposed for the Dunham Dolomite. The view is from the basin looking westward towards the craton. The units underlying the Dunham Dolomite are shown on the sides of the block diagram. The Dunham is shown onlapping the Cheshire Quartzite to the west, providing a source for the sand found in the Dunham. The Peritidal, Subtidal/Open Shelf, Channel and Platform Margin Facies are shown arrayed perpendicular to depositional strike, with the St. Albans Reentrant responsible for local variation in facies and thicknesses. See Figure 1 for locations. See Figure 4 for symbols.

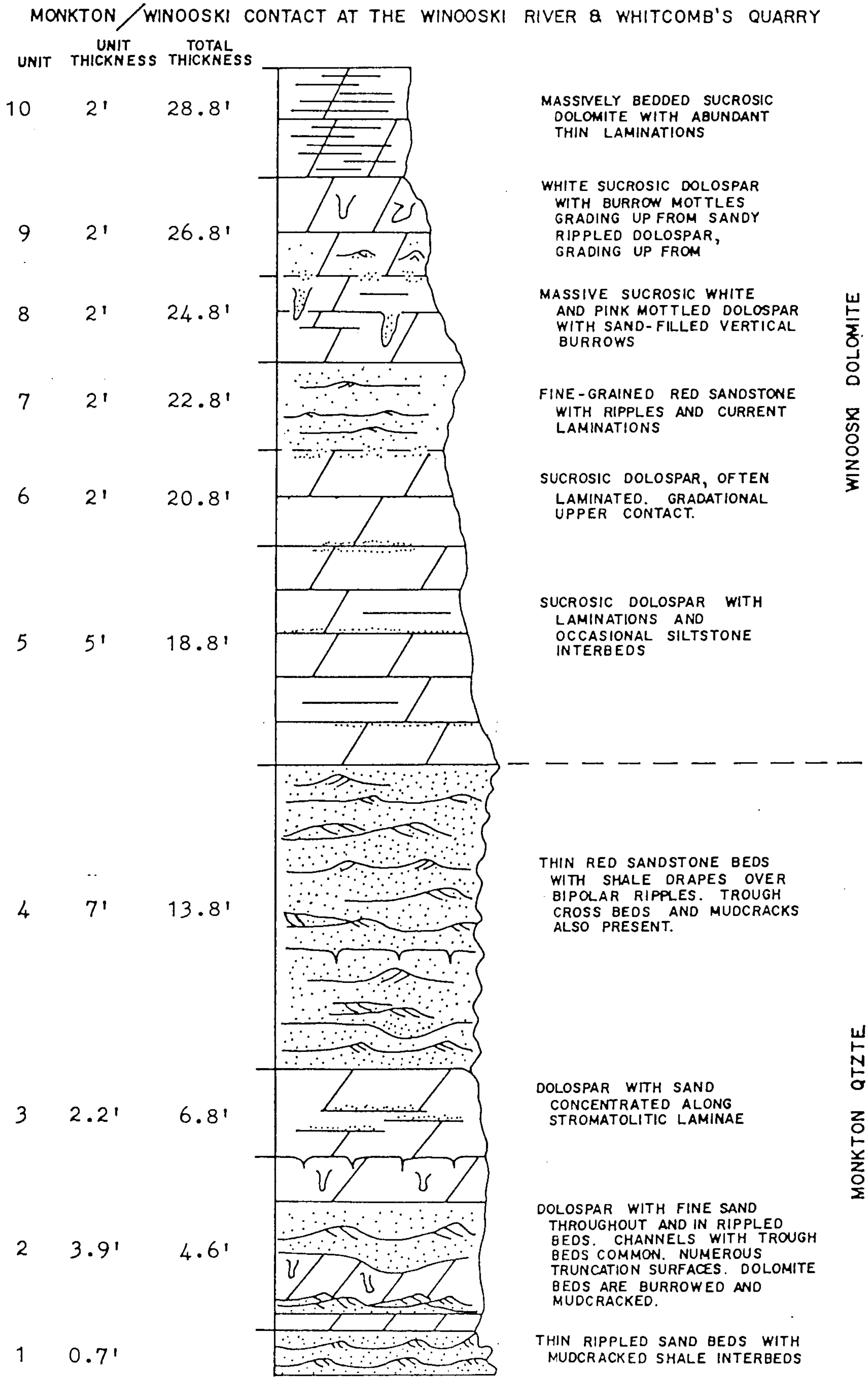
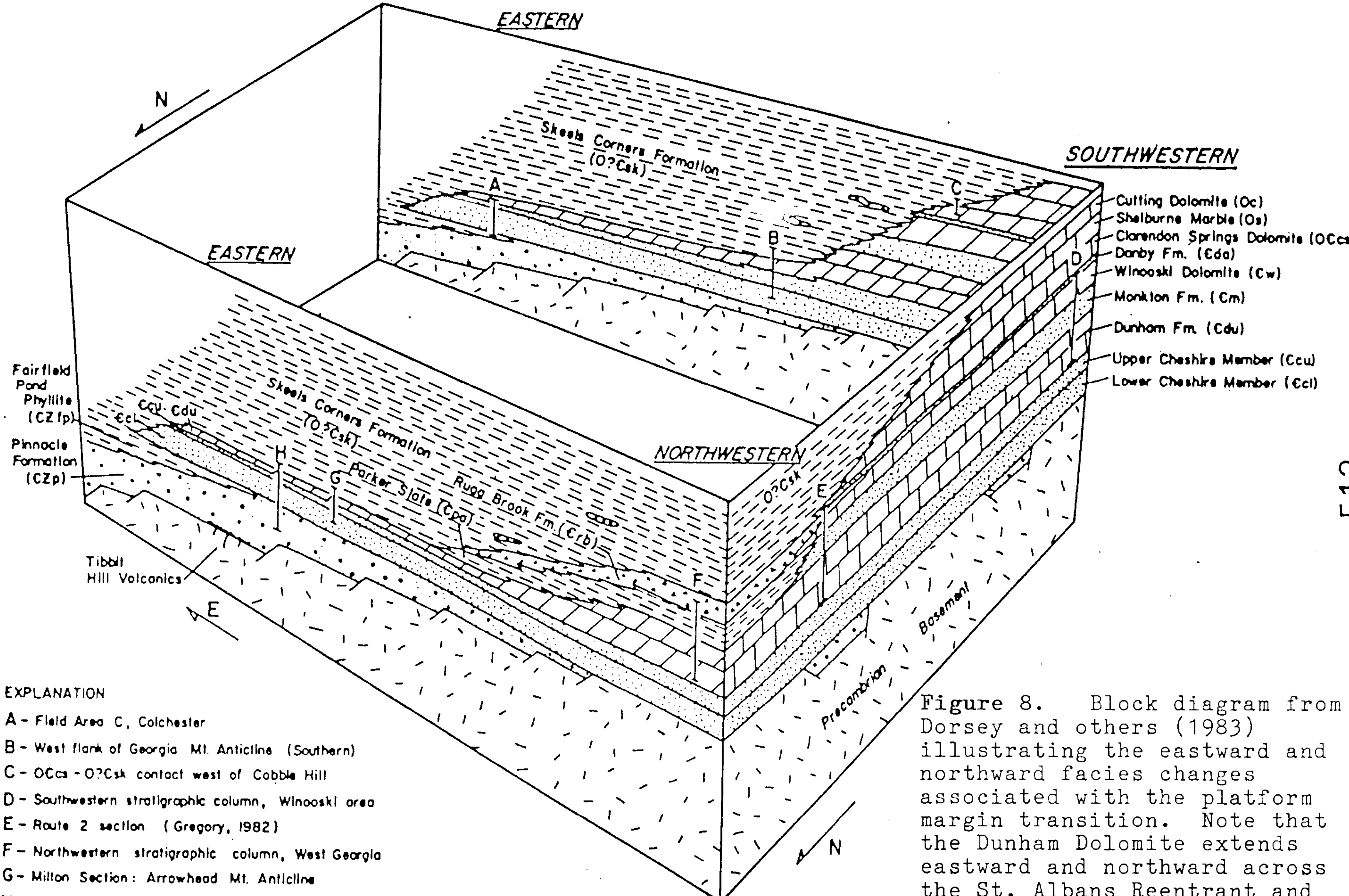


FIGURE 7. Measured stratigraphic section of the contact between the Monkton Quartzite and Winooski Dolomite as exposed in a quarry in Winooski.



EXPLANATION

A - Field Area C, Colchester

B - West flank of Georgia Mt. Anticline (Southern)

C - OCcs - O?Csk contact west of Cobble Hill

D - Southwestern stratigraphic column, Winooski area

E - Route 2 section (Gregory, 1982)

F - Northwestern stratigraphic column, West Georgia

G - Milton Section: Arrowhead Mt. Anticline

H - West flank of Georgia Mt. Anticline (Northern)

Figure 8. Block diagram from Dorsey and others (1983) illustrating the eastward and northward facies changes associated with the platform margin transition. Note that the Dunham Dolomite extends eastward and northward across the St. Albans Reentrant and into the adjacent basin whereas all subsequent units accrete vertically to the west.

ooski Dolomite over an interval of 5 meters. The ratio of siliciclastic sand to dolomite changes over this interval and ultimately passes into stromatolitic dolomite characteristic of the Winooski Dolomite.

WINOOSKI DOLOMITE

The environments of deposition and lithofacies of the Winooski Dolomite have not yet been studied in detail. The Winooski has been studied only by virtue of its position between the Monkton and Danby quartzites (Mehrtens and others, 1983). Unpublished studies on the Winooski Dolomite (Mehrtens) suggest that it is composed of the following lithofacies: 1) interbedded rippled fine sand and silt with minor clay and dolomite; 2) dolomite with planar cryptalgalaminite structures; 3) dolomite with LLH stromatolites reaching a height of 50 cm; 4) dolomite with disseminated quartz sand; 5) quartz arenite beds with a dolomite matrix; 6) polymictic breccia beds with a matrix of dolomite and quartz-rich dolomite. No shallowing-up cycles have yet been recognized within the Winooski Dolomite.

Lithofacies (1), (2), (3), (4) and (5) are arranged in a vertical sequence along the Winooski River. Lithofacies (1) and (2) are interbedded with the underlying Monkton Quartzite and are interpreted to represent Peritidal deposits. Lithofacies (3), (4) and (5) make up the bulk of the stratigraphic section along the river, and due to an absence of any obvious sedimentary structures, are also interpreted as shallow subtidal in origin. Lithofacies (4), (5) and (6) are recognized in the Winooski Dolomite to the east and north. In the absence of any sedimentary structures these are interpreted to represent Subtidal and Platform Margin deposits, respectively. This interpretation is supported by the similarity of these lithofacies to those of the Monkton and Dunham formations. These lithofacies occur in the same paleogeographic position as the Subtidal and Platform Margin lithofacies of the Dunham and Monkton formations. This occurrence is evidence for the post-Dunham localization of the shelf margin, the result of upward growth rather than basinward progradation. In the south and west the Winooski Dolomite is gradationally and conformably overlain by the Danby Quartzite. The base of the Danby is recognized as the first massive bed of quartz arenite (Butler and Mehrtens, 1985).

DANBY QUARTZITE

The Danby Quartzite is a 35-80 meter thick mixed siliciclastic-carbonate unit. Near its type section in southern Vermont the Danby is characterized by a siliciclastic basal unit and an upper carbonate unit termed the Wallingford Member. To the north the Danby thins and becomes a mixed siliciclastic-carbonate unit composed of interbedded quartz arenite, pure dolomite, dolomitic sandstone and sandy dolomite. Four lithofacies have been identified by Butler and Mehrtens (1985): Intertidal to Shallow Subtidal, Subtidal, Open Shelf and Platform Margin. The Inter- to Shallow Subtidal Facies is characterized by interbedded sandy dolostone, quartzose sandstone and shales with mudcracks, vertical burrows, wave and current ripples, cryptalgalaminites and oncolites. The Subtidal sediments are composed of thick bedded sandy dolostones and pure dolostones with herringbone cross stratification. The Outer Shelf Facies is characterized by thick bedded, coarse-grained dolomitic sandstones and quartzose sandstones with large scale tabular cross stratification. Platform Margin deposits are composed of polymictic breccias in a dolomite matrix.

The Danby Formation is interpreted to represent sediments deposited on the Cambrian platform in a complex mosaic of deposits representing fairweather and storm processes. Evidence for storm deposition is exhibited in the Inter- to Shallow Subtidal Facies, where laterally discontinuous bedding, erosional downcutting surfaces, hummocky cross stratification, and graded bedding are common.

Preliminary analysis of thickness data and siliciclastic/carbonate ratios within the Danby suggest that a siliciclastic source existed to the south and west of northwest Vermont. The siliciclastic material within the Danby is texturally mature quartz sand, suggesting that the clastic source is either an older sedimentary rock (Cheshire, Monkton quartzites) or extremely reworked detritus of a contemporary deposit (Potsdam Sandstone).

The Danby is overlain by the Clarendon Springs Dolomite and Shelburne Marble, determined by Shaw (1949) and Keith (1923) as Lower Ordovician in age. The sedimentology of these units has not been studied in any detail; however Dorsey and others (1983) determined that a conformable, gradational contact existed between the Clarendon Springs and Skeels Corners Shale as exposed in the vicinity of Cobble Hill and Munson Flats.

PLATFORM GEOMETRY

Figure 8, taken from Dorsey and others (1983), summarizes the geometry of the Cambrian platform in northwestern Vermont. Several important features include: 1) the existence of the St. Albans Reentrant; 2) the facies similarity between the Eastern Basinal Sequence and the St. Albans Reentrant facies; 3) the distribution of the Dunham Dolomite over the entire platform, followed by westward retreat and localization of the platform margin in late or post-Dunham time; 4) the localization of the platform margin throughout Cambrian time.

Evidence of the St. Albans Reentrant and the similarity of these facies to those in the Eastern Basinal Sequence has been presented earlier. It was also mentioned earlier that the St. Albans Reentrant is thought to have originated as a foundered graben on the rift margin. Timing of the initial foundering is based on the observation that the Monkton, Winooski and Danby formations (all post-Dunham units) pinch out and pass into basinal shales and conglomerates (Fig. 9) both to the north and east. The Dunham Dolomite is the only platform deposit which continues across the St. Albans Reentrant, suggesting that the St. Albans Reentrant had not yet been established in Dunham time. The geometry of the St. Albans Reentrant must have been established during late or post-Dunham time. Additional evidence for this includes an analysis of the distributions of Dunham facies. The Dunham Dolomite in its most easterly exposures (Franklin, subsurface; Colchester Pond) is more argillaceous than exposures to the west; the Peritidal Facies is also thinner, and shallowing-up cycles are less numerous (Dorsey and others, 1983; Mehrtens, unpublished data). This suggests that the basal, older Dunham Dolomite passed gradationally eastward into the adjacent basin as a carbonate ramp, with no development of Platform Margin deposits. Although no supporting biostratigraphic evidence exists, it is suggested here that by middle Dunham time vertical accretion rates landward on the platform (westward) were keeping pace with thermal subsidence rates, and the carbonate sediment began to build vertically, establishing the carbonate platform.

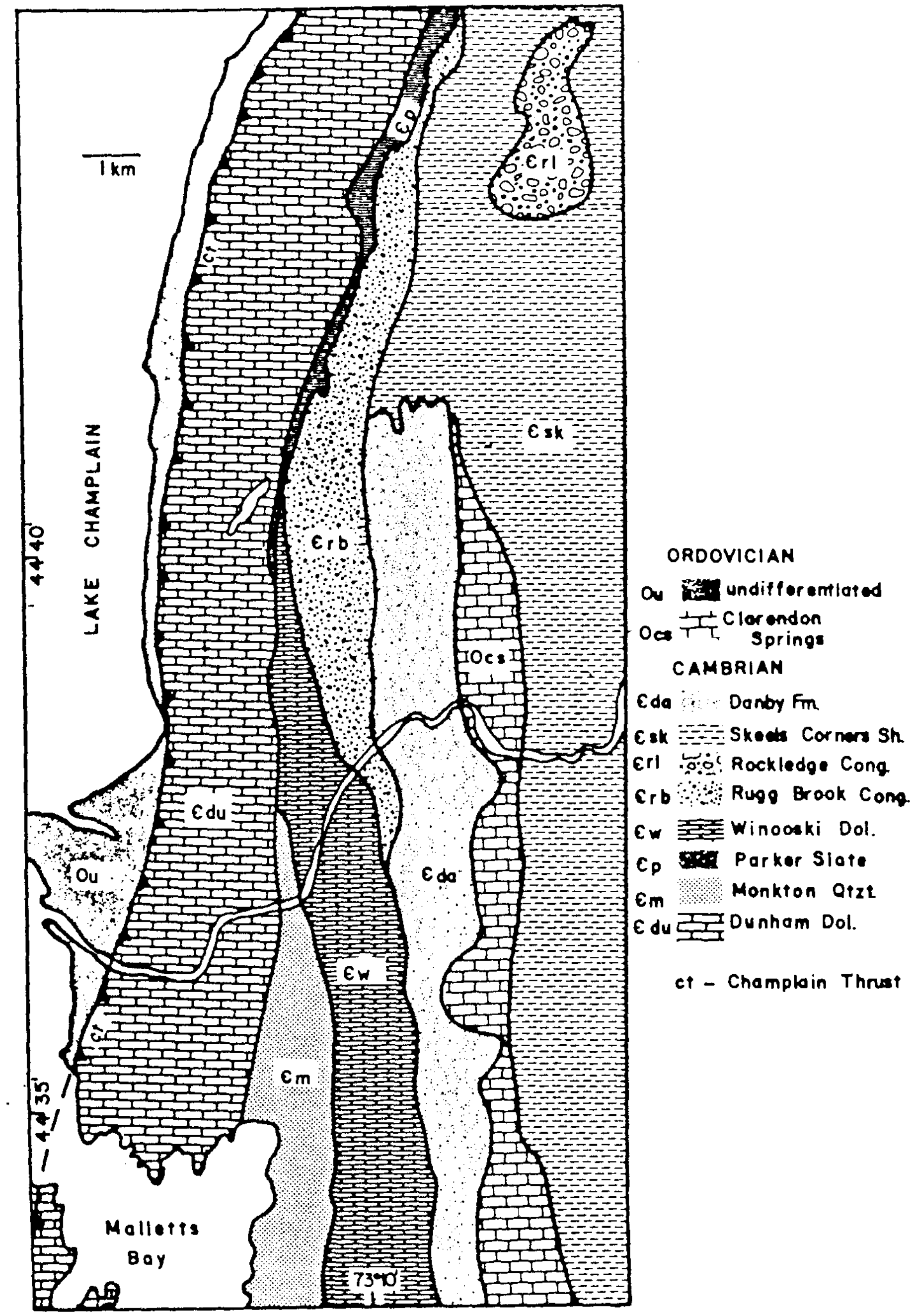


Figure 9. Geologic map of a portion of the State Geologic map illustrating the pinchout of the shelf facies to the north of Malletts Bay. This pinchout defines the southern margin of the St. Albans Reentrant.

Lower carbonate sedimentation rates to the east led to the eventual abandonment of the carbonate platform in this region, and basinal sediment was subsequently deposited. For the same reason, the St. Albans Reentrant must have also subsided at this time. Following this proposed westward shift in the position of the carbonate platform, the geometry of the carbonate platform was stable throughout the remainder of the Cambrian. Evidence for this is based on the localized occurrences of Platform Margin Facies (oolites, breccia horizons) for successive rock units (Dunham, Monkton, Winooski, Danby formations).

SUMMARY

The sedimentology of four of the five Cambrian shelf units have been studied in detail (Cheshire, Dunham, Monkton, Danby quartzites). Of these, all but the Cheshire record Peritidal to Shallow Subtidal and Platform Margin Facies. The facies of the Cheshire appear to represent a shallow siliciclastic "blanket" over the Eocambrian rift topography. The Dunham Dolomite represents the initial carbonate unit on the newly formed shelf and the sedimentary facies recognized within this unit are found within subsequent formations as well. Upward building of the carbonate platform during Dunham time resulted in the development of a platform to platform margin transition characterized by the abrupt pinch-out of shallow water facies into basinal shale deposits. This facies change is recognized in both the eastern and northern regions of the Cambrian outcrop belt in all units studied.

ACKNOWLEDGMENT

This paper is dedicated to Brewster Baldwin, Middlebury College, in recognition of his longstanding support of "soft rock" geology in Vermont.

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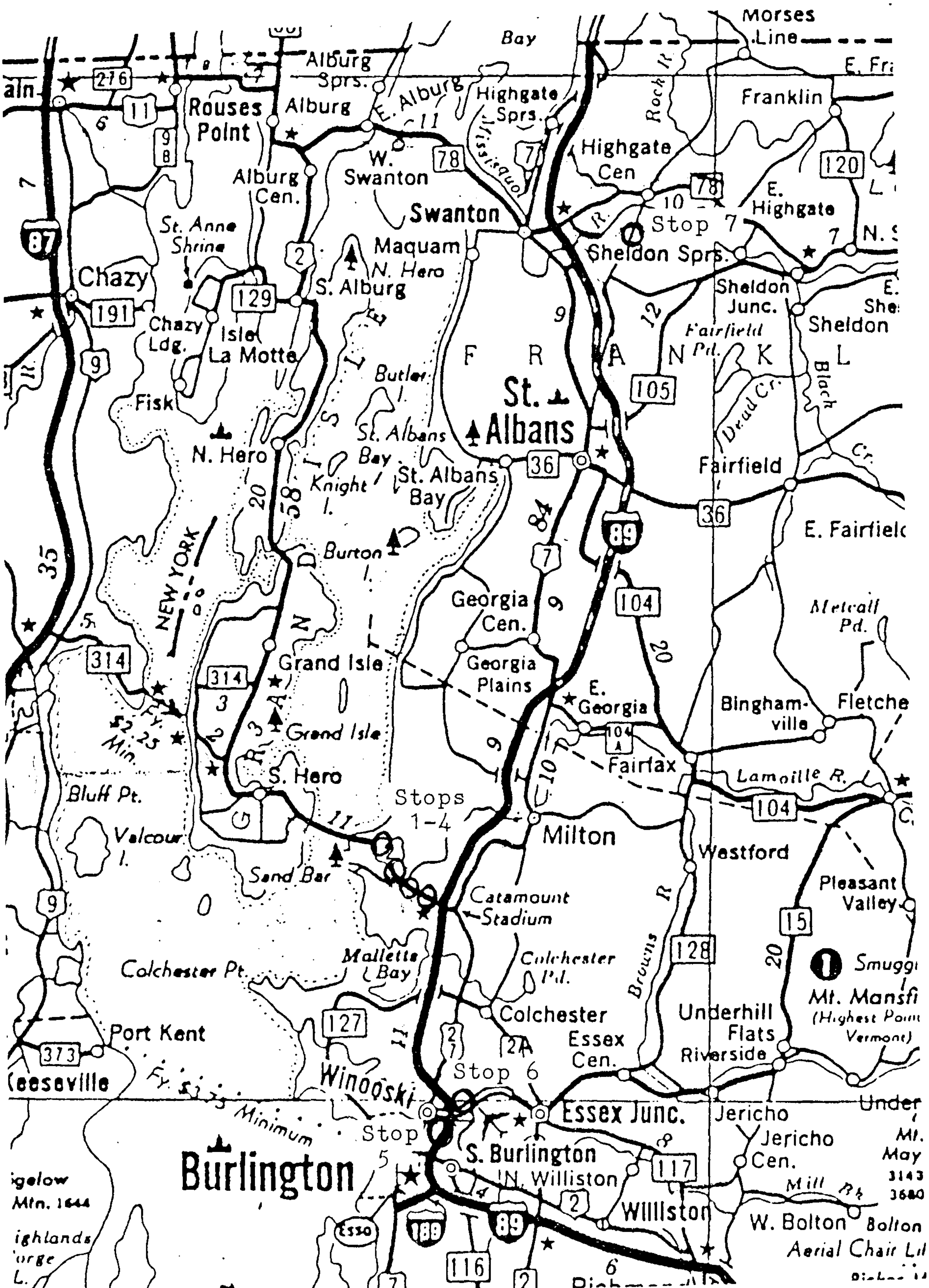


FIGURE 10. Road map showing field stops.

ROAD LOG

Field trip starts from parking lot behind Perkins Geology, University of Vermont. Mileages are cumulative from that point. Roads are shown in Figure 10.

0.0 Leave UVM parking lot, drive down Colchester Ave. to Interstate 89 entrance in Winooski. Head north to Champlain Islands, Route 2 exit. Head eastbound.

Stop 1. Quarry. Dunham Dolomite - Peritidal Facies

8.4 Abandoned quarry on north side of Route 2.

As you walk up the driveway into the quarry, note that the floor of the quarry consists of black shale. You are standing on the Stony Point Shale, Middle Ordovician in age. The Champlain thrust forms the floor of the quarry: the Dunham Dolomite of the walls above has been thrust westward some 80-100 km to its present position on top of the Middle Ordovician shales. Do not climb on the walls of the quarry as they are very unstable: there are enough blocks lying around to look at. The Dunham Dolomite exposed here is the basal Peritidal Facies, characterized by the sedimentary boudinage of interbedded dolomite (white) and silt-rich dolomite (red). This bedding style is thought to be the product of alternating deposition of carbonate and clastic laminae, with subsequent differential compaction causing boudings. There is local imbrication of the boudins. Examine the contacts between the white dolomite and the red silt-rich dolomite; flowage lines are visible which indicates a soft-sediment deformation history. Many of the white dolomite pods are not boudins, but burrows. How can you tell the difference? The repetitive interbedding of carbonate and clastic sediments, local imbrication of clasts, and vertical burrowing are all characteristics which suggest that these sediments formed in the Peritidal environment (somewhere in the tidal range).

Return to cars and drive east on Route 2, back towards the interstate. Dunham exposures along road.

Stop 2. Dunham Dolomite - Shallowing-up Cycles

9.0 Pull off on right hand side of road beyond Bear Trap Road intersection. Carefully cross the road to the roadcut on the north side of Route 2.

This roadcut exposes three shallowing-up cycles present within the lower half of the "middle" Dunham. Present within an SUC is a basal unit of the Subtidal Facies (bioturbated dolomite) overlain by sedimentary-boudinaged beds of the Peritidal Facies (the same bedding style as seen at Stop 1). In the lower SUC the contact between these two facies is gradational: there is an interval between the Subtidal and Peritidal Facies in which the sediment becomes progressively more silt and clay rich and the rhythmic interbedding develops. Other cycles further up in this roadcut do not exhibit this gradation but go directly from Subtidal sediments to those of the Peritidal. What is the significance of SUC's? They record the lateral, basinward migration or aggradation of tidal flat sediments into the adjacent subtidal. Why does this occur cyclically? They must record the interplay of sediment supply, sea level and basin subsidence.

Return to cars and continue driving east.

9.3 Note exposures of Dunham (Subtidal Facies) with the characteristic color mottling.

9.5 Cross the Lamoille River.

9.8 Another large roadcut of the Subtidal Dunham

10.1 Clay Point Road intersection.

Stop 3. Dunham Dolomite - Subtidal and Platform Margin Facies

10.2 Long roadcut, pull off about 100 yards beyond speed limit sign.

At the base of this outcrop (west end) are good exposures of the Subtidal Facies of the Dunham, with characteristic mottled texture produced by burrowing. Specimens of *Salterella conulata*, an obscure fossil, can be found here. The color difference in the Dunham was attributed by Stone and Dennis (1964) to varying percentages of trace metals. At the east end of the outcrop the uppermost facies of the Dunham is exposed: the Platform Margin Facies with its characteristic polymictic breccia. The breccia clasts sit in a sandy dolomite matrix and interbedded graded beds are present. These beds are interpreted to be debris flows in origin (structureless, poorly sorted) with interbedded turbidites (Bouma division A). The coarseness of the sandy dolomite matrix, the angularity and size of the clasts, and the absence of shale suggests that this breccia formed immediately adjacent to the platform margin. The final stop of this field trip exhibits Platform Margin deposits which are characteristic of more distal, basinal environments.

10.6 Raymond Road intersection

Stop 4. Monkton Quartzite - Subtidal and Shelf Edge Facies

10.9 Long roadcut on the south side of Route 2 in the Monkton Formation.

This roadcut exhibits the Subtidal and Shelf Edge Facies of the Monkton (in other words, not the basal beds of this unit). The thickness of beds, thickness of sandstone/shale and sandstone/silt couplets, and the height of cross beds are indicative of a shelf (subtidal shallow water) setting. These characteristics can be compared to those of the Monkton at the next stop (Salmon Hole). Walk east to the small knoll beyond the road sign. This is the polymictic breccia characteristic of the Monkton Shelf Edge Facies. Note that the clasts are polymictic, with sandstone and dolomite clasts present. The matrix is a coarse-grained quartz arenite. There is no outcrop above this; however the Shelf Edge Facies of the Winooski Formation is exposed at an outcrop on Route 7 immediately at the "T" junction with Route 2. These breccia occurrences are important because they mark the southern extent of the intrashelf basin, the St. Albans Reentrant.

11.2 Return to cars and take I-89 southbound.

15.0 Monkton all along this stretch of I-89.
Note how different the beds look than at Stop 4.
As you drive progressively south you go into the tidal flat sediments of the Monkton. This indicates that the tidal flat was prograding northward into the open shelf adjacent to the St. Albans Reentrant.

17.6 First outcrops of the Winooski Dolomite.

17.7 Exit 16 south off I-89.

17.9 Go south on Rts. 2 and 7. Winooski Dolomite on your right and entrance to Whitcomb's Quarry, where the Monkton/Winooski contact is exposed.

19.0 Go right at "Y", staying on Rts. 2 and 7.

Stop 5. Salmon Hole. Monkton Quartzite - Intertidal Facies

19.2 Sign on right for Salmon Hole. Pull off.
Additional parking across the street. Descend path to river.

After descending path to the Winooski River you come out on large bedding planes of red rippled sandstone beds of the Intertidal Facies of the Monkton Quartzite. This outcrop is very near the top of the unit: the covered interval upstream covers the contact with the Winooski Dolomite across the river and upstream. It is important to note that unlike the Dunham, the top of the Monkton is a very shallow water deposit. This again reflects the fact that the Monkton records a prograding tidal flat. Whereas in the Dunham the progradation was restricted to the shallowing-up cycles, in the Monkton overall sediment supply was so much higher that progradation of the entire unit occurred. This outcrop exhibits many of the bedforms characteristic of siliciclastic tidal flats: interbedded rippled sand with shale drapes, mudcracks, vertical and horizontal burrows. At the top of the Monkton is a massive buff dolomite bed interpreted as a supratidal dolomite (carbonate mud washed up onto the tidal flat). Remember that in a siliciclastic tidal flat the carbonate comes from offshore (open shelf) while the quartz sand comes from an adjacent land source.

The Monkton /Winooski contact is under water here but is exposed in Whitcomb's Quarry a few miles to the north. Over an interval of approximately 30 feet the percentage of carbonate in the Monkton increases: the uppermost bed of the Monkton is defined as the last pure quartzite bed. The lowest beds of the Winooski have abundant quartz disseminated throughout, decreasing in percentage up section. The entire Winooski Dolomite is exposed on the north side of the river. If water levels permit you can walk through the entire section up into the Danby Quartzite.

LUNCH

After lunch return to cars and proceed to the next stop, which is upstream on the Winooski River, above Stop 5.

Stop 6. Champlain Mill. Danby Quartzite - Monkton Quartzite contact.

19.4 Drive back across the bridge and turn into the Champlain Mill parking lot.
Go to the lot below IGA.

Depending on the level of the river you can walk from the Winooski Dolomite on the banks below the Champlain Mill apartments through a covered interval and into the Danby Quartzite below the Mill shopping center. The contact of the Winooski Dolomite and Danby Quartzite is gradational in nature. The Winooski consists of sucrosic dolomite with stromatolites (the large humps on the bedding plane below the bridge) and variable amounts of disseminated quartz. The base of the Danby is recognized as the first bed of dolomitic sandstone. On the Winooski River the Danby displays many of the same bedding features seen in the Monkton Quartzite below. Bedding planes of rippled sands with carbonate mud drapes are common. Rippled up stromatilites (oncolites) are present. This outcrop exhibits some of the best examples of ripple morphologies associated with storm-influenced sedimentation (wave ripple bundles).

Before leaving the Winooski River outcrop, note that the facies present in all rock units (Monkton, Winooski, Danby formations) record sedimentation in Supra- to Intertidal to shallowest Subtidal. None of the facies seen earlier along Route 2 are present. This distribution of facies reflects the south-to-north facies change produced by the basin in the north, the St. Albans Reentrant. The final stop will display some of the features associated with basinal sedimentation.

Return to cars and head north on Rts. 2 and 7 to the northbound I-89.

Stop 7. Rockledge Formation - Basinal Deposits

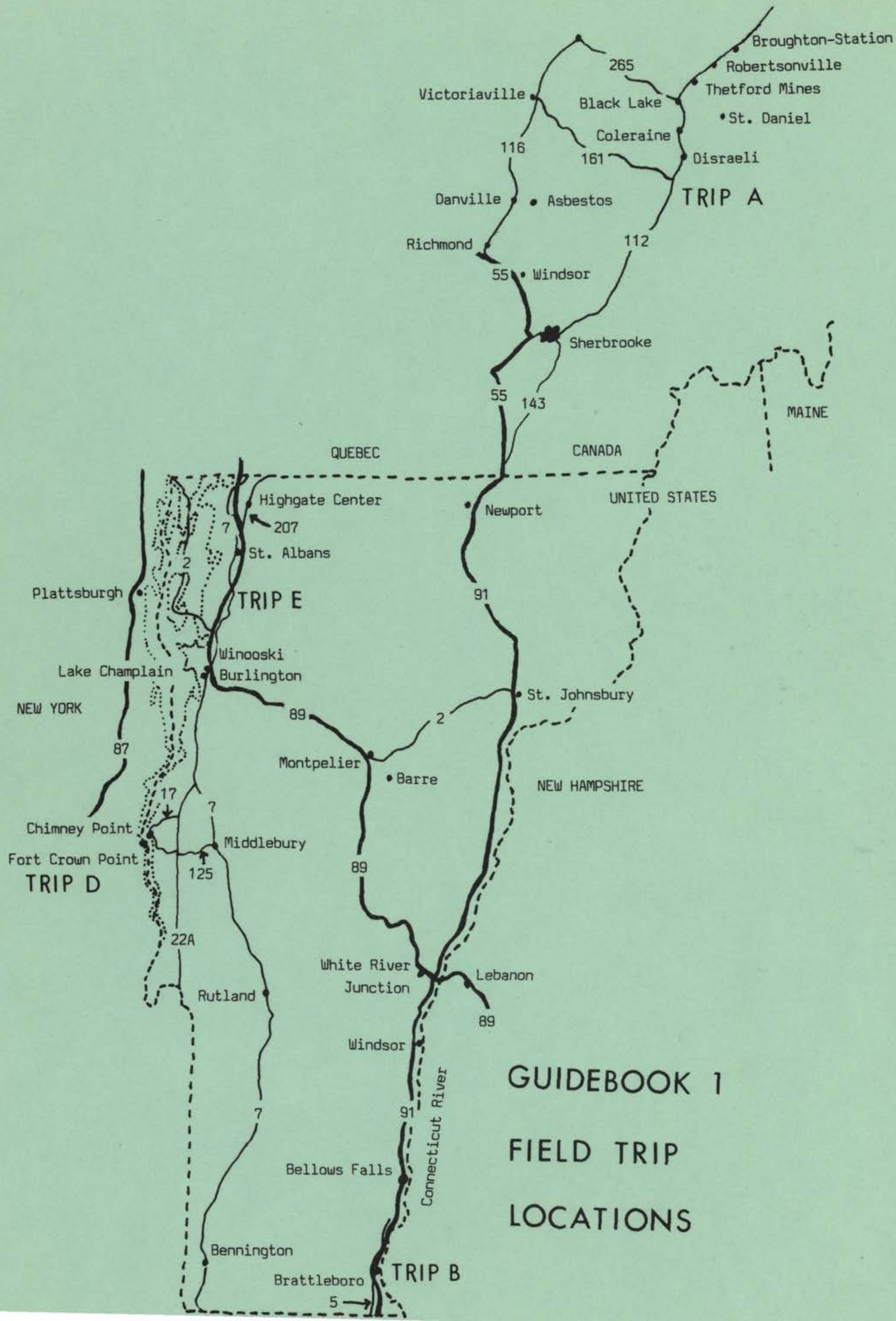
47.6 Exit in St. Albans at Exit 20. Turn right and head north on Route 207.

49.4 Proceed north on Route 207 to farmhouse. Park in driveway.
BE SURE TO ASK PERMISSION TO VISIT THIS OUTCROP!!
Head for the west side of the knoll to the south.

This ridge displays several facies of the Rockledge Formation, a late Middle Cambrian - Upper Cambrian basinal deposit, probably deposited on a submarine fan. Compare the features at this outcrop to those seen at Stops 3 and 4, where the more proximal facies of Platform Margin deposits were seen. Note that these deposits look less chaotic, in other words, not like the "talus" piles seen on Route 2. Here it is possible to see that the debris flows exhibit imbricated clasts and are crudely graded. Contacts between flows, with downcutting, erosional bases are present. The clasts are dominantly recrystallized limestones and sandy limestones. The matrix is also quartz sand-rich lime mud. If time permits, this ridge can be followed to the south and turbiditic shales are seen. On the other side of the barbed wire fence a limestone breccia in a shaley matrix is seen. This facies of the Rockledge Formation is important because it records what a debris flow does when it flows over an incompetent substrate; the shale must have been fluidized (soupy) and easily incorporated into the flow as it passed. If you sketched the lateral facies changes in this outcrop alone you would see these different facies along the same stratigraphic level. This is a small example of what is seen on a larger scale in the St. Albans Reentrant; facies pass laterally from turbiditic shales to conglomerate horizons of variable composition. A portion of the St. Albans quadrangle is currently being remapped in detail to establish the nature of these lateral facies changes.

79.0 Return to cars and drive back to Burlington.

END OF TRIP



GUIDEBOOK 1

FIELD TRIP

LOCATIONS