GEOLOGICAL ASSOCIATION OF CANADA
NEWFOUNDLAND SECTION

FROM THE INTERTIDAL ZONE TO THE UPPER MANTLE – THE AMAZING GEOLOGY OF GROS MORNE NATIONAL PARK

October 2-6, 2003

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Welcome to the 2003 Fall Field Trip

The Newfoundland Section of the Geological Association of Canada welcomes participants to our 2003 Fall Field Trip, and to the scenic and geological wonderland of Gros Morne National Park. Gros Morne National Park is, without question, the preeminent "geological attraction" in the Province of Newfoundland and Labrador, and is considered by many to be the best location anywhere in the Appalachians to understand several important aspects of their geological evolution in a single small area. Newfoundland geologists might well argue that the Lower Paleozoic stratigraphy of the Laurentian margin is revealed better in the Port-au-Port area, or that the Betts Cove ophiolite is better-preserved and more complete than those of the Tablelands, but these are not the key issues. Gros Morne represents a special place where many disparate and unique elements of Newfoundland geology came together hundreds of millions of years ago, and were then further sculpted during the Ice Age and postglacial times. Here, geological processes and geological time created a place where amazing geology and spectacular natural beauty coexist. It is the combination of these features, coupled with unusual plant life, abundant animal life and a rich human history, that makes this park so remarkable, and which attracts growing numbers of visitors each year. It is thus an opportune and appropriate time for a field excursion of this type, and for the initial preparation of a guidebook that we hope will be of lasting value to professional visitors.

We hope that you all enjoy this field trip, and that the beautiful Indian Summer of 2003 will continue through the first weekend of October. Please take a few moments to read the introductory material on safety and procedures, and remember that Gros Morne National Park is a protected area in which we must take only photographs and leave only footprints.

Welcome to Gros Morne National Park of Canada

The rocks of Gros Morne National Park and adjacent parts of western Newfoundland are world-renowned. Within the park's boundaries are rock exposures, geological suites, and fossil assemblages that are of international significance, and have attracted geologists from around the world.

In 1987, mainly as a result of its geological features, Gros Morne National Park was designated a World Heritage Site by UNESCO (United Nations Education, Scientific, and Cultural Organization) under criterion

(i) "be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of land forms, or significant geomorphic or physiographic features"

and

(iii) "contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance"

In support of its nomination the significance of the park's geology was described as follows.

> "The park is internationally acclaimed for its complete portrayal of the geological events that took place when the ancient continental margin of North America was destroyed by plate movement, complete with the emplacement of a large relocated portion of oceanic crust and ocean floor sediments. Collectively, these features are comparable to the best locations in the world."

This diverse geology and superlative glacial features of the area have resulted in a spectacular landscape and created a diversity of ecosystems and plant life unique to western Newfoundland. As part of a system of over 40 national parks across Canada, Gros Morne National Park protects a representative example of this unique part of the Canadian landscape and the geological features it contains.

We hope you enjoy this exceptional opportunity to explore Gros Morne National Park and learn more about its fascinating geology from some of the people that have been instrumental in furthering our understanding of this place. Through activities like this field trip that presents the significance of this place, Canadians can appreciate, understand and benefit from our natural heritage.

SAFETY

The Geological Association of Canada (GAC) recognizes that its field trips may involve hazards to the leaders and participants. It is the policy of the Geological Association of Canada to provide for the safety of participants during field trips, and to take every precaution, reasonable in the circumstances, to ensure that field trips are run with due regard for the safety of leaders and participants.

Footwear – GAC recommends steel-toed safety boots when working around road cuts, cliffs, or other locations where there is a potential hazard from falling objects. GAC will not supply safety boots to participants. Some field trip stops require sturdy hiking boots for safety. Field trip leaders are responsible for identifying any such stops, making participants aware well in advance that such footwear is required for the stop, and ensuring that participants do not go into areas for which their footwear is inadequate for safety. Field trip leaders should notify participants if some stops will require waterproof footwear.

Field trip participants are responsible for:

Acting in a manner that is safe for themselves and their co-participants.

Using personal protective equipment when necessary (when recommended by the field trip leader or upon personal identification of a hazard requiring PPE use).

Informing the field trip leader of any matters of which they have knowledge that may affect their health and safety or that of co-participants.

Hazards:

Most of the stops are reached by paved road from which they are easily accessible by foot, by either well-defined trails or short scrambles. The visit to the Tablelands ophiolite will involve a walk of about 6 km, for those who participate.

Care should always be taken when visiting any site, especially those adjacent to the coast, where the hazard of falling debris from the slopes above is a real one. In such situations, we advise participants not to put themselves in jeopardy by attempting to ascend such slopes, and to maintain a safe distance.

In coastal settings, participants may be vulnerable to freak waves, and should maintain a safe distance from the high water line.

Weather is unpredictable and participants should be prepared for a wide range of temperatures. Always take suitable clothing. A rain suit, sweater, sturdy footwear are essential at almost any time of the year.

Do not walk straight down steep slopes if others are also on the slope below. Instead, proceed down slopes at an angle.

Several stops are adjacent to highways, and participants must take great care in crossing them. Groups crossing together are particularly vulnerable, and each individual must take responsibility for their own safety.

There is little likelihood of encountering wild animals. Although late in the year, black flies may be present, and participants may wish to carry repellent.

Some stops are at the top of steep cliffs or slopes. Participants should stay well back from the cliff edge at all times. Overhangs are common on unconsolidated cliffs, and often are not visible from above.

GUIDELINES FOR LOCALITIES IN GROS MORNE NATIONAL PARK

It should be noted that collecting is not allowed within the Park boundaries without a permit.

This applies to rock and mineral samples, and to fossils, and also applies to plant life. The use of hammers on outcrop surfaces is also unacceptable, as this may damage features of interest.

ACKNOWLEDGMENTS

The 2003 GAC Fall Field Trip was assisted greatly by grants from the Association of Professional Engineers and Geoscientists of Newfoundland (APEGN), the St. John's 1988/2001 Trust Fund, and Cornerstone Resources. The logistical support and vehicles supplied by the Geological Survey, Department of Mines and Energy, was also invaluable. Student participation was assisted by Department of Earth Sciences, Memorial University.

GENERAL INTRODUCTION

The pre-Carboniferous rocks exposed in and about Gros Morne National Park, western Newfoundland, fall into six main groups. These are described below, from structural bottom to top. The letters below correspond to those used to label the map in Figure 1.

A) Grenvillian basement rocks, mainly assorted gneisses and other plutonic rocks cut by late Precambrian mafic dykes. These are an extension of the Canadian Shield. The western margin is locally an overthrust, which brings these above Lower Paleozoic rocks discussed below.

B) A sequence of late Proterozoic to Cambro-Ordovician mainly shallow-water sedimentary rocks that sit unconformably on the basement. The older parts of the sequence locally include near-basal late Proterozoic volcanic rocks, Lower Cambrian shales, sandstones and limestones and an overlying Middle Cambrian to Middle Ordovician carbonate shelf sequence with deep-water carbonates at the top, overlain by an upper flysch succession.

C) A series of deep-water Cambrian and Ordovician sediments, the Humber Arm Supergroup, disposed in a series of tectonic slices separated by mélange.

D) An extremely well-preserved sequence of latest Precambrian alkaline olivine basalts, agglomerates and other volcanogenic sediments, known as the Skinner Cove Formation

E) A complex of strongly to little deformed group of ultramafic to silicic igneous and metamorphic rocks with associated minor deep-water chert and shale, collectively known as the Little Port Complex.

F) A tectonically disrupted mafic and ultramafic massif of Early Ordovician age that shows a classic ophiolitic igneous, metamorphic and sedimentary stratigraphy. This is known as the Bay of Islands Ophiolite, and forms the structurally highest component of the area.

Figure 1 is a sketch map of the distribution of these groups, which also shows the locations of the field trip stops in the park. Figure 2 is a stratigraphic chart that shows locations of field stops.

The main purpose of this trip is to demonstrate some of the evidence for the current interpretation of the above assemblages as a telescoped Cambro-Ordovician continental margin capped by slabs of material derived from oceanic regions that lay beyond the continental realm.

The first day of the field trip will examine the basement rocks (A), some overlying sedimentary rocks (B) and provide an introduction to Park geology. The second day will examine autochthonous sedimentary rocks (B) and allochthonous sedimentary rocks (C) that represent their deep-water time-equivalents. The third day will examine allochthonous sedimentary rocks (C) and overlying ophiolitic rocks (E and F). Unfortunately, time does not permit examination of the Skinner Cove Formation (D).

Note that weather conditions may force us to switch days 2 and 3, and tidal conditions may necessitate some revision of stop sequences for coastal localities.

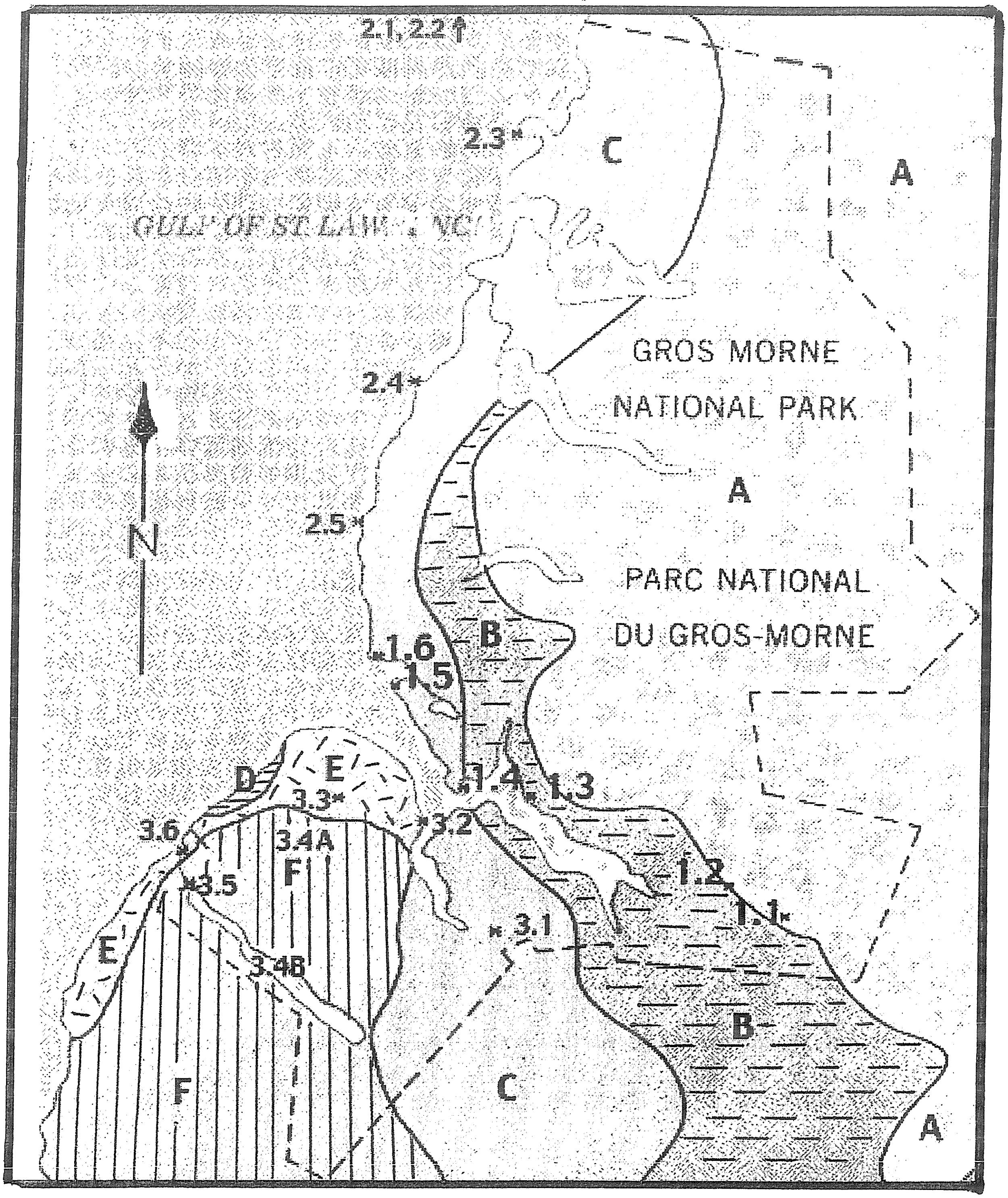


Figure 1a. *The major geological components of Gros Morne National Park and surrounding areas, and the approximate location of field trip stops within the park. For explanation of units A to F, see the text.*

Legend

Movement of Thrust Sheets

Melange

Amphibolite and greenschist

Allochthonous Rocks

Bay of Islands Complex

Pillow Basalt and Sheeted Dykes

Gabbro

Peridoite

Little Port Complex; *gabbro, dykes, pillow basalt, trondhjemite, shale*

Lower Head Formation; *sandstone, conglomerate, shale*

Cow Head Group; *limestone conglomerate, thin-bedded limestone, shale, chert*

Curling Group; *shale, quartzite, and conglomerate*

Skinner Cove Formation; *basalt, pillow basalt, trachyte, volcanic breccia*

Autochthonous Rocks

Goose Tickle, Cape Cormorant Formations; *shale, sandstone, minor limestone conglomerate*

St. Georges, Port au Port Groups; *limestone and dolomite*

Labrador Group; *sandstone, quartzite, shale, minor conglomerate and limestone*

Long Range Complex; *granite and gneiss cut by diabase dykes*

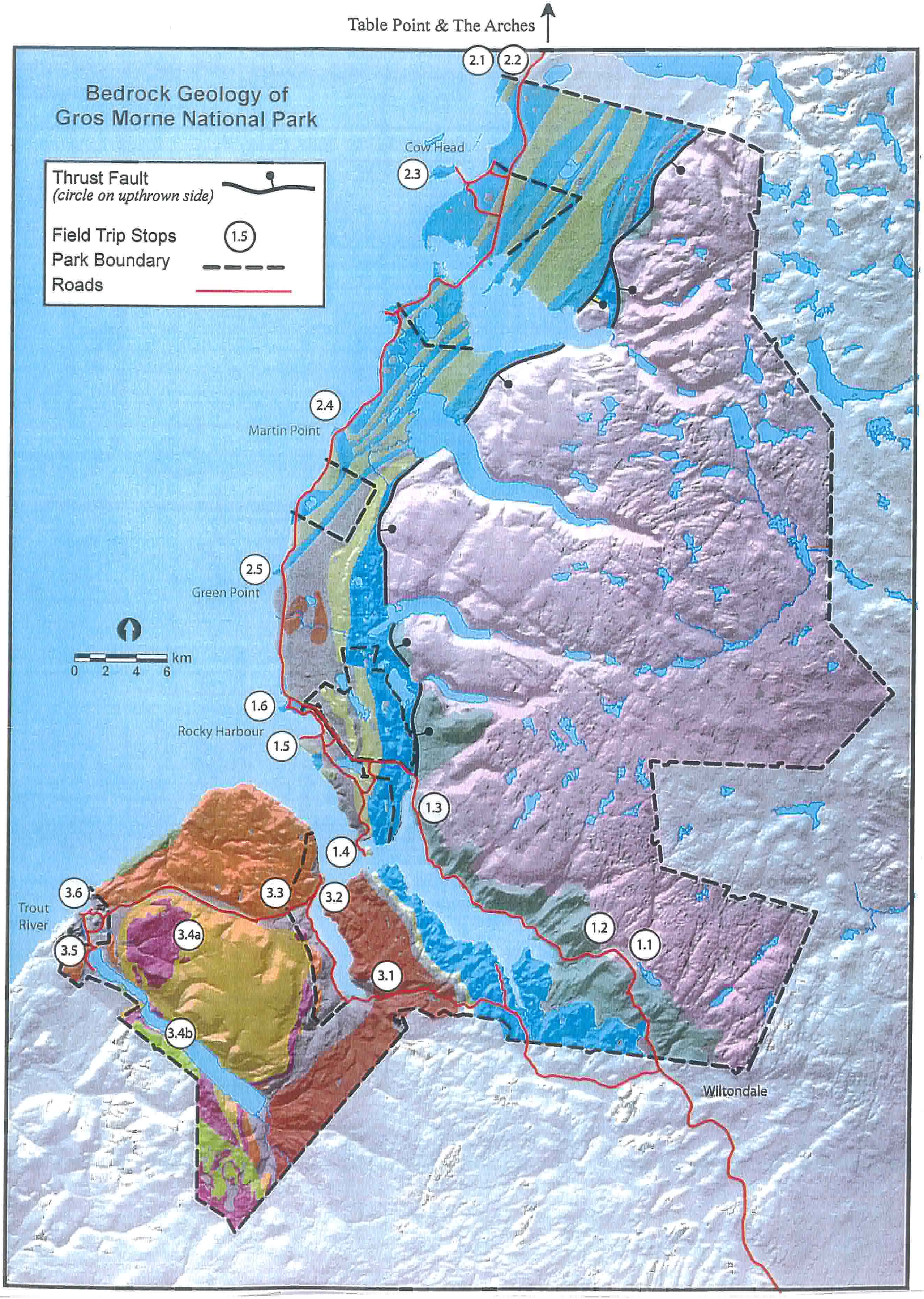


Figure 1b. *Simplified geology of Gros Morne National Park and surrounding areas. Based on the simplified map included in Berger* et al. *(1992), compiled by R.K. Stevens. Colour map produced by R. Hingston and Parks Canada.*

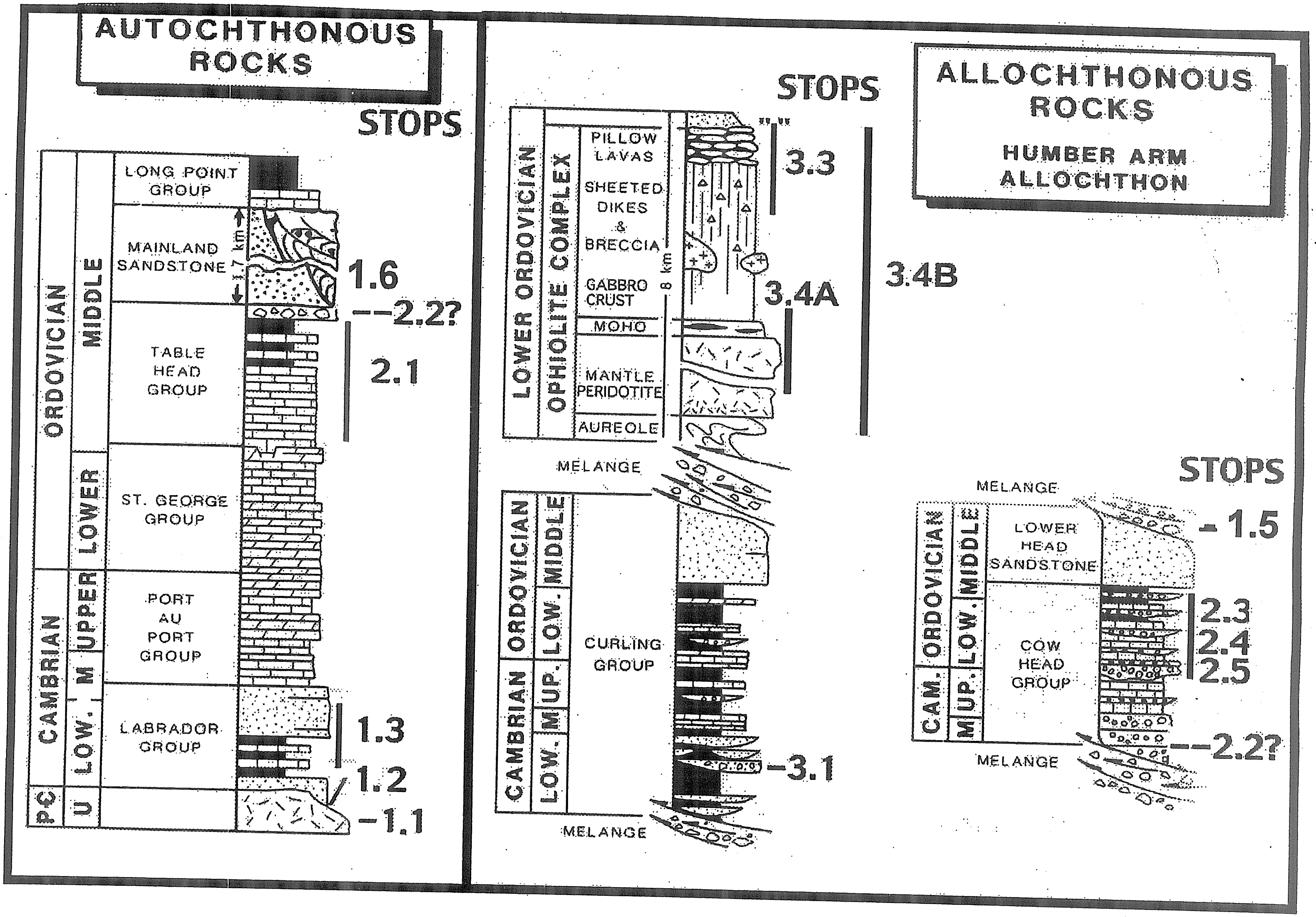


Figure 2. *Approximate stratigraphic locations of the field trip stops. See text for more details. Stratigraphic charts are from James et al. (1988, 1989).*

DAY ONE – THE BASEMENT, AUTOCHTHONOUS ROCKS, MÉLANGES AND AN OVERVIEW OF PARK GEOLOGY

Leader: Robert K. Stevens

Note: Weather, tides and time will control the itinerary of this field trip. Expect changes from the following outline.

INTRODUCTION

Day one of the trip will visit the Precambrian–Cambrian unconformity and the oldest autochthonous sedimentary rocks exposed in Gros Morne National Park. It will also provide an overview of the various components of park geology, and visit important outcrops at Lobster Cove Head, which were critical in the initial understanding of the allochthonous nature of the ophiolite sequences for which the Park is now most famous. We will also visit examples of the mélanges that facilitated long-distance transport of the Humber Arm Allochthon.

Stop 1-1
Precambrian Basement of the Long Range Inlier
WARNING! WATCH FOR TRAFFIC!

The stop is located about 8.6 km north from the Route 430/431 junction in Wiltondale. Park in a turnout on the right hand side of the road, on a long downhill stretch, near a "Test Brakes" sign. Walk a short distance back up the hill. There are outcrops on both sides of road, but those on the left hand (west) side are better. The larger outcrops in the long roadcut further down the hill are actually less informative.

The Grenville basement rocks are here dominated by a medium-grained, grey to greenish, metaplutonic rock, with a strong epidote–chlorite alteration, and many greenish epidotized fracture surfaces. The gneiss contains a simple penetrative fabric, and there is generally no sign of banding or dykes. This rock type is invaded by coarse-grained, pink, K-feldspar-rich granite veins, which also contain a variably developed fabric. The southern end of the outcrops contain some areas of banded gneiss, perhaps representing older enclaves.

Stop 1-2
Precambrian–Cambrian Unconformity
WARNING! WATCH FOR TRAFFIC!

The road cut is about 9.5 km north from the Route 430/431 junction in Wiltondale, just past the sign indicating the hiking trail to Southeast Brook. The long outcrop on the right hand side of the road exposes basement rocks, which are essentially identical to Stop 2, but not as well-preserved, and overlying Lower Cambrian conglomerates, sandstones and carbonate rocks of the Labrador Group. The unconformity itself is located about 25 m uphill from the sign.

The basal terrigenous clastic rocks of the Bradore Formation (Labrador Group) are thin here (<10 m), and pass upwards into the overlying Forteau Formation. The base of the latter is marked by a fossiliferous limestone unit containing numerous thin shale and siltstone beds, known as the Devil's Cove Member. The unconformity is marked by a thin, irregular conglomeratic unit, in which most clasts are <2 cm in size. The unconformity surface is rather irregular, and fissures or depressions are filled with coarser grained conglomerate, containing boulder-sized granite clasts. The overlying purplish sandstones of the Bradore Formation are magnetic.

The unconformity marks about as much time as that which has passed from the start of the Cambrian to the present, a time during which most metazoan life evolved.

Stop 1-3
Forteau Formation
WARNING! WATCH FOR TRAFFIC!

The journey from Stop 1-2 to Stop 1-3 passes along strike through outcrops of the Hawke Bay and Forteau Formations (Labrador Group), including sandstones, quartzites, siltstones, shales and minor limestones. Note the massive steel rock bolts, a precaution against rock slides. These are needed because the rocks dip towards the road.

Stop 1-3 is located about 29 km from the Route 430/431 junction in Wiltondale, on the right hand (east) side of the road, on a downhill section just before a small causeway across a lake. The location also provides good views of Gros Morne. The outcrop forms a large west-dipping bedding plane, and there is a sign warning against painting the rocks.

At this stop, the formation is dominated by shales and siltstones. The outcrop contains the large trilobite *Olenellus thompsonii*, but specimens can be faint and hard to see in poor light.

Gros Morne Mountain (806 m asl) is the highest point in the Park, but not the highest point in Newfoundland. The Lewis Hills are just 9 m higher. The top of the mountain consists of resistant quartzites of the Hawke Bay Formation.

The dark peak to the right of Gros Morne ("Old Crow") consists of Precambrian gneisses and granites; the notch between the two mountains is a high-angle fault that juxtaposes cover and basement.

Just north from here, around the bend, the road crosses the trace of a thrust fault that brings the Grenville with its cover of Cambrian sediments over younger platformal carbonate rocks. Most of East Arm (Bonne Bay) marks the trace of this fault. The Grenvillian Long Range Inlier and its Cambrian cover are allochthonous in this area. A locally developed flat slatey cleavage and recumbent folds are associated with the thrust. Landscaping by the Park authorities has covered over the best of these outcrops. Movement along the thrust is relatively small (a few tens of kilometres) compared to movements of hundreds of kilometres and more along the mélanges and dynamothermal metamorphic zones that bound the higher structural slices of the Humber Arm Allochthon and the ophiolites.

It is not clear exactly how the East Arm thrust connects with the thrust that brings the Long Range over shales with a flat cleavage exposed along Highway 430 north of the Cormack Junction. Nor is the age of the thrusting well established. It is usually thought to be of Acadian age but there is no evidence that the faults bounding the Long Range Inlier/massif are not Carboniferous structures.

Stop 1-4
Panoramic Views from Norris Point

This stop is located near the MUN Marine Station in Norris Point. Continue north on Route 430, and take the road sign posted for the Park Interpretation Centre. Go past the centre, and turn left at the Norris Point–Rocky Harbour road. Proceed to the Marine Station at the end of the road, and park behind the building. Walk west along the road by the seashore for a short distance to a small hill at the end of the road. From here, you can see virtually every element of the geology of the park. The panorama is illustrated in Figure 3, reproduced from Berger *et al.*, 1992.

Looking south from the hill top, the rocks to your right are transported while those to your left are parautochthonous.

The lookout is located near the base of a mélange unit, which marks the base of the Humber Arm Allochthon, consisting of sedimentary, volcanic and plutonic rocks that have been transported westwards across the ancient continental margin of Laurentia. The lower structural slices are dominated by sedimentary rocks, including deep-water assemblages developed on the continental slope; the upper slices consist of the ophiolites, i.e., dismembered pieces of oceanic crust and mantle, probably developed in a back-arc basin within the Iapetus Ocean.

To the east, the grey rocks are autochthonous and parautochthonous quartzites and sandstones that we have just visited under Gros Morne and Killdevil. The flat-topped hills in the far distance are the Precambrian basement, which unconformably underlies these rocks.

Steeply dipping, light-grey cliff faces, some 200 m high, on the south of Bonne Bay represent the autochthonous carbonate platform sequence of the Table Head Group, but are more deformed than equivalent localities to be visited upon Day 2.

To the west of these cliffs, the mélange zone separating autochthon and allochthons passes through lower-lying, wooded country. To the right of the prominent meadow, hilly forested country is largely underlain by deep-water siliciclastic rocks and minor volcanic rocks belonging to the lower part of the Humber Arm Allochthon.

A second, structurally higher, belt of mélange separates the sedimentary slices from the upper structural slices of the allochthon, which makes up most of the mountains in the distance. It continues along the South Arm of Bonne Bay. The prominent conical peak (Peak of Tenerife) above the village of Glenburnie consists of metamorphic rocks (mostly amphibolites) that form part of the dynamothermal aureole beneath the ophiolite proper. The name "Peak of Tenerife" was assigned by

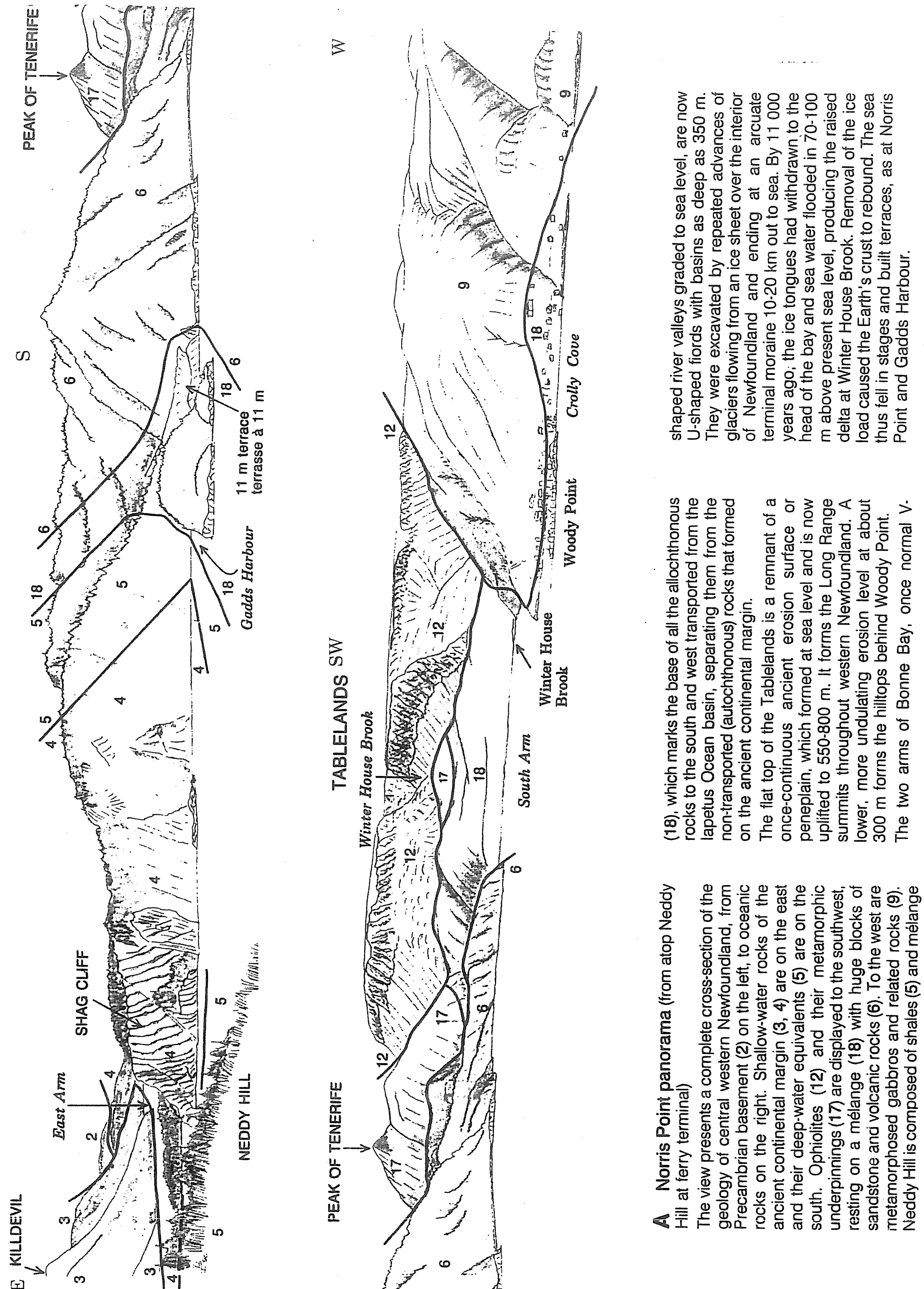


Figure 3. *Panoramic view from near the MUN Marine Station in Norris Point. Original drawing and bilingual caption from Berger* et al. *(1992). The original drawing was by Ian Brookes.*

the explorer Captain James Cook, and reflects its distinctive conical shape, which reminded him of the huge caldera that defines the profile of the volcanic island of Tenerife, in the Canary Islands.

The ultramafic rocks of the Tablelands ophiolite form the high red-brown mountains directly across Bonne Bay. The absence of vegetation reflects the toxic (and nutrient-poor) nature of the peridotites and other ultramafic rocks that dominate the Tablelands.

The darker, more vegetated Lookout Hills directly to the west include gabbro, trondhjemitic granitoid rocks and some mafic volcanic rocks, all part of the ocean-derived assemblage of the Little Port Complex.

Large fault scarps visible on the upper reaches of the Lookout Hills are believed to be of postglacial origin, and record its slipping towards Bonne Bay after the melting of the supporting glacier. This is the largest known unsupported sag in Canada.

The only significant component of the Humber Arm Allochthon that is not seen in this panorama is the Skinner Cove assemblage that outcrops on the other side of the high peaks of the Little Port Complex. The Skinner Cove assemblage consists of Eocambrian volcanic rocks that possibly record the initial rifting stage of the Iapetus Ocean (Cawood *et al.*, 2001).

Stop 1-5
Mélanges at Rocky Harbour

The stop is located near the fish plant in Rocky Harbour. Drive 10.2 km north from the Marine Station to Rocky Harbour, and turn left. Drive a farther 1.5 km to the fish plant. The outcrops are on the beach just below the parking lot. They consist of chaotic material with a shaley matrix and numerous broken beds, and are just one small part of an extensive zone that marks the base of the Humber Arm Allochthon in this area. Better mélanges are visible along shore to the east, and will be visited if time permits.

A note on mélange formation and associated movement of fluids

Mélanges were first recognized in the Humber Arm allochthon by Stevens (1965) where there were described as zones of chaotic deformation. They were not called mélanges at that time because the type mélanges in Anglesey, Wales, were widely regarded as sedimentary slump deposits.

In contrast, the zones of chaotic deformation associated with the Humber Arm Allochthon were clearly a result of deep-seated movement sub-parallel to bedding. It was suggested that the mélanges were formed by near frictionless movement across zones of load-induced high hydrostatic pressure. Water was the main fluid involved but the common association of mélanges and bitumen suggested that hydrocarbons were mobile as well. The latter probably occur because much of the matrix of the mélange is derived by incorporation of distal slope to basin plain green and black shales, which are rich in organic carbon. The algae *Gloeocapsamorpha prisca* provides this organic-rich source in allochthonous Early Paleozoic sequences of western Newfoundland (Fowler *et al.*, 1995).

The chaotically deformed zones often have marginal facies in which a ghost stratigraphy is preserved.

The phacoidal (i.e., numerous small lenses) structure, which characterizes the mélanges, is thought to have developed because water was lost, and friction increased during emplacement and assembling of the allochthon. It is notable that the lenses are often striated across their short axis, parallel to the direction of later stages of movement. As dehydration proceeded, friction increased and eventually the zone locked, forcing movement to transfer to a newly overpressured zone in a more recently accreted, lower part of the assembling allochthon. The allochthon accreted slices at its base, analogous to snow sticking to the underside of a sledge as it moves, so that in a very general way, the higher the slice in the allochthon the farther it has moved.

The rare occurrence of limestone having fossil tube worms in the uppermost pre-flysch part of the sedimentary section suggests that hydrocarbons such as methane were vented to the sea floor in front of the allochthons. Fluids moving in front of the Taconian allochthon may have carried metals that were deposited to form the Daniels Harbour zinc mineralization although Lane (1990) concluded that mineralization occurred during regional fracturing related to Acadian deformation.

Stop 1-6
Lobster Cove Head–Cow Head Group and Lower Head Formation

The Lobster Cove Head lighthouse, which is a new Parks Canada Exhibit Centre, was commissioned in 1898. Our stop is along the cliffs beneath the lighthouse. The outcrops are best seen when the tide is low.

Drive 4.9 km north from the fish plant (Stop 1-5) through the town of Rocky Harbour. Turn right from the unpaved road at the sign posted access road to the lighthouse. Follow the trail, and descend to shore on the first stairway. Walk south on the shore up the sedimentary section, returning by the second, not the first, stairway to the south.

Lobster Cove Head is one of the critical localities in understanding the geology of Gros Morne National Park, and has been visited on several previous field trips. The following description is adapted and simplified from James *et al.* (1988).

This entire area is an intact sequence of Lower to Middle Ordovician strata that forms a huge floating raft within the mélange zone that surrounds Rocky Harbour. The basal part of the section is a distal facies of the Cow Head Group and can be correlated with parts of the Cow Head Peninsula (to be visited on Day 2) on the basis of both faunal assemblages and rock types. However, the upper part of the section, dominated by interbedded dolostone and shale, is distinct from all other parts of the Cow Head Group. These strata are interpreted to have formed down slope from a drowned platform margin, as turbidites of mud and detrital dolomite. The contrast between these two environments is indicated by Figure 4 (from James *et al.*, 1988).

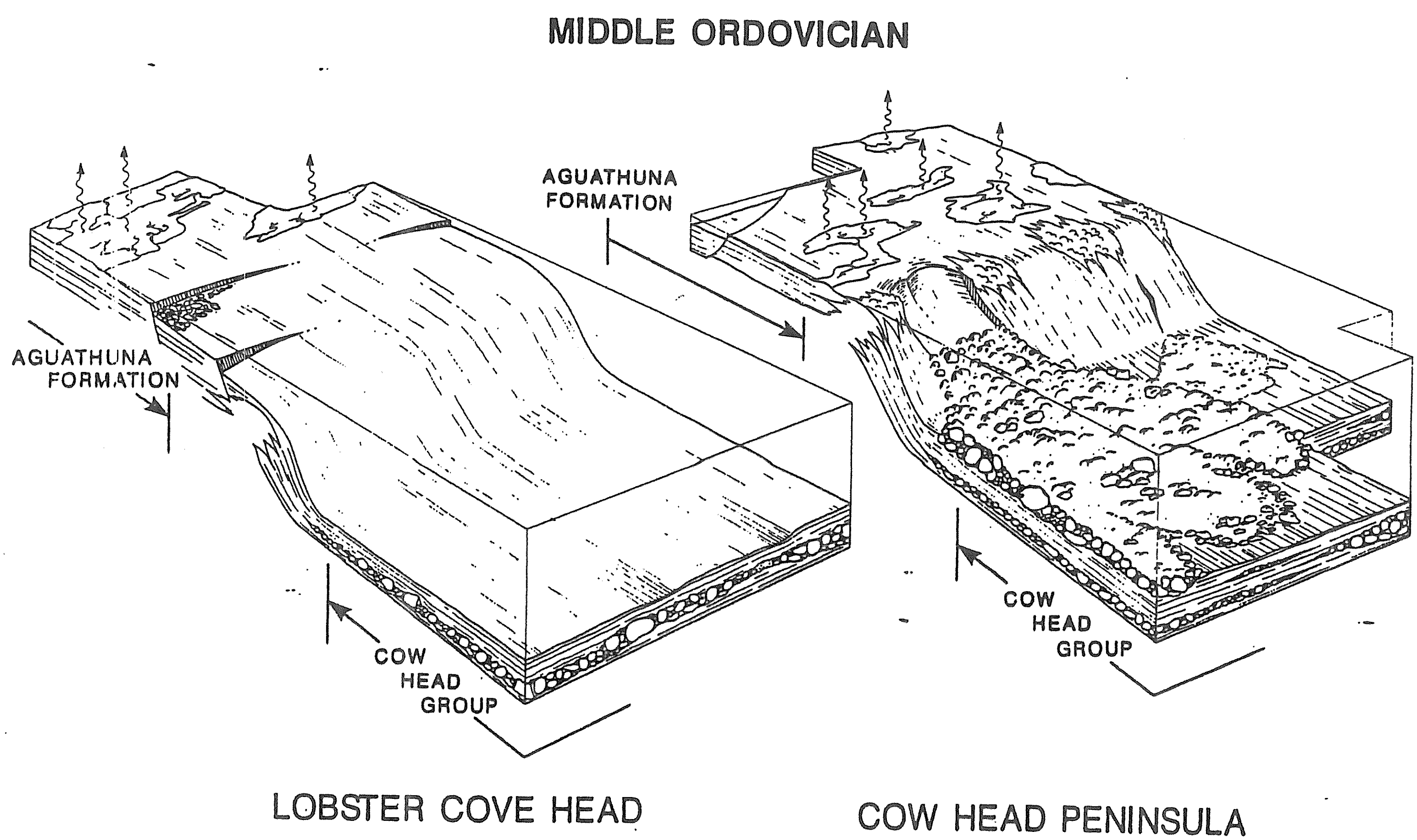


Figure 4. *Conceptualized models of the platform margin at Cow Head (adjacent to a shallow-water platform) and Lobster Cove Head (adjacent to a drowned platform) during early to middle Ordovician time (late Arenig–early Whiterock). From James* et al. *(1988).*

The break up and drowning of the platform, as well as facies changes in the upper part of the Humber Arm, are thought to record the westwards passage of a peripheral bulge across the old Laurentian margin associated with an east-dipping subduction zone located far to the east.

The highest part of the section consists of greywackes of the Lower Head Formation that represent flysch derived by erosion of the approaching allochthons. Below the base of the Lower Head Formation, there are beds of dolostone and shale, similar to the underlying rocks, which have been disrupted, locally rotated, and injected by the sandstone dikes and sills. The lithology of these injected sediments is similar to that of the overlying Lower Head Formation indicating that the earliest deformation and emplacement of the deep-water sequences occurred when the sediments were still unconsolidated or semiconsolidated. The sills mimic bedding. Disrupted contacts of this type are common at the base of the Lower Head Formation elsewhere in the Humber Arm Allochthon and are also seen at comparable contacts in Quebec. The green sandstones of the Lower Head Formation contain detrital chromite, which was derived from the ultramafic rocks of the allochthons.

DAY TWO – AUTOCHTHONOUS AND ALLOCHTHONOUS SEDIMENTARY ROCKS, FROM THE CONTINENTAL SHELF TO THE CONTINENTAL SLOPE AND DEEP OCEAN

Leader: Robert K. Stevens

Overview

The obducted ocean floor exposed on Table Mountain is certainly the best-known and most visibly appealing aspect of the geology of Gros Morne National Park, but the park and nearby areas also contain sequences of sedimentary rocks, which are equally noteworthy and perhaps more interesting than the ophiolites. They are little-appreciated, yet their study yielded vital clues to the assembly and emplacement of the allochthon, and to understanding the complex interplay of tectonics and sedimentation in the Taconian foreland basin of western Newfoundland. Indeed, the very recognition of the igneous rocks as transported ophiolites rather than intrusive complexes depended in part on the discovery of chromite and serpentine grains in the sediments. In addition to the significant petrology of the Taconian flysch, the flyschoid sediments preserve 1) a record of near-edge continental margin environments that are rarely preserved anywhere in the geological record, and 2) a record of a segment of Middle Ordovician time that is represented by unconformities over much of the rest of North America. Furthermore, these rocks include the Green Point section, which is designated as the World Stratotype for the Cambrian–Ordovician Boundary.

Geological Background

The sedimentary rocks to be seen on Day 2 fall into two groups: The autochthonous rocks are assigned to the Table Head Group. The transported (allochthonous) rocks are part of the Cow Head Group, which is part of the Humber Arm Allochthon. The stratigraphic relationships are indicated in Figure 2.

The Table Head Group is a succession of carbonate rocks that was deposited on the foreland side of the Taconian foreland of western Newfoundland during partial subduction of the ancient continental margin of North America. It is a deepening-upwards sequence of limestones and shales that nicely demonstrates Walthier's Law of Facies Succession, that is, the vertical sequence of facies mimic the horizontal distribution of facies at any one time.

In this particular sequence of rocks, this law is reflected in the upward change in the succession from a basal unit of nearshore, peritidal cyclic carbonates to subtidal open shelf carbonates to deep-water, shaly slope carbonates to basinal shales. More simply put, it means that as the shelf sinks, deeper water facies migrate onto the former platform in the order that they were distributed out to sea. As you go up section, you cross facies boundaries as if you were traversing farther out to sea.

In the case of the Table Head Group, however, this orderly succession of facies and stratigraphy is encapsulated in the evolving development of a tectonically dynamic foreland basin. During the late Arenig and the Llanvirn (Late Early to Middle Ordovician), active extensional faults, which mostly trend northeast (Stenzel *et al.*, 1990, Waldron *et al.*, 1993, Cooper *et al.*, 2001) helped fashion not only the karst terrain of the underlying St. George Unconformity, but divided the regional foreland basin into a collage of subbasins and arches. During deposition of the Table Head Group, this led to impressive variations in both the local thickness of stratigraphic units and the distribution of carbonate facies in the various stratigraphic units of the group (Stenzel, 1992, Stenzel *et al.*, 1990). This dynamic reached its zenith as the carbonate shelf foundered and was smothered by easterly-derived clastic flysch. Work by Stenzel (1992) indicates that in some areas of the basin, stromactactis mud-mounds and high-energy crinoid–brachiopod–?bryozoan calcarenites signalled local shallowing of the shelf in its terminal phase. In other places, basinal shales rest disconformably upon fractured and mineralized shelf carbonates suggesting rapid drowning.

Most spectacular, however, are bodies of limestone conglomerate that occur within the autochthonous flysch of the overlying Goose Tickle Group. These conglomerates were derived by erosion of uplifted carbonates of the Table Head Group. In some instances, the conglomerates are tens to hundreds of metres thick and in each case they are deposited in subbasins that formed in the hangingwall of syndepositional growth faults adjacent to arches that exposed the Table Head Group. Evidence on Port au Port Peninsula indicates that some of these faults exposed carbonates of the Cambrian to Lower Ordovician passive shelf, effectively allowing up to 1000 m of erosional incision locally and contributing the polymict conglomerates of the Cape Cormorant Formation. On the Great Northern Peninsula, the carbonate conglomerates consist of debris derived only by erosion of the Table Head Group. The best of these conglomerates include nut-sized pebbles to house-sized blocks of limestones of the Table Point and Table Cove formations and are beautifully exposed at the harbour in Daniels Harbour, near Portland Creek Pond and river and in roadcuts along highway 430 near Rocky Harbour. It is designated the Daniels Harbour Member of the Goose Tickle Group (Stenzel *et al.*, 1990, Quinn, 1995). In recent interpretations of the foreland basin of western Newfoundland, these conglomerates predict the presence of inversion faults of Acadian or younger age (previous growth faults) and point to potential structural/stratigraphic traps for hydrocarbon exploration in the footwall (Cooper *et al.*, 2001).

In the early days of geological research, however, these conglomerates of the Daniels Harbour Member and Cape Cormorant Formation led to much confusion because these rocks at the top of the autochthonous sequence greatly resemble older transported rocks of the Cow Head Group, which were deposited in deep water along the continental margin (*see below*).

The Cow Head Group is part of the Humber Arm Allochthon, and its rocks formed on the lower parts of an ocean-facing continental margin and adjacent continental slope during Cambrian and Lower Ordovician times. These rocks are the deep-water time equivalents of the shallow-water carbonate rocks exposed elsewhere in western Newfoundland, and have been transported eastward over the latter. Such rocks are only very rarely preserved in the geological record in essentially unmetamorphosed and undeformed condition.

All indications are that the Cow Head Group was derived from a long-lived and extensive source that lay to the northwest in present coordinates. The fact that no such source now exists, nor is there space for one, is one argument for the allochthonous nature of the Cow Head. It should also be noted that the depositional trends of both the transported and autochthonous sediments have a similar trend that is slightly more EW and oblique to the regional NE-SW structural trend.

Essentially the Cow Head Group is a condensed sequence of deep water shales that represent most of the time between the late Middle Cambrian and early Middle Ordovician. Every so often, the slow deposition of shales was rudely interrupted by massive debris flows of limestone blocks and less powerful flows of limestone turbidites. All of the blocks in a given flow were essentially coeval and derived from different parts of a carbonate bank and ocean-facing slope. Any one conglomerate bed is therefore a sampling of numerous coexisting bank and slope environments. At least one block at Lower Head is over 50 m across. However, most of the geological time involved in the stratigraphic section is related to the deposition of the shales.

The debris flows pass into turbidites down slope and can be thought of as energy pulses that sweep down the continental slope. Close to the source, the load is boulder-sized chunks of the bank and bank edge. During down-slope transport, these larger clasts are redeposited, but material from lower down slope is ripped up and incorporated into the flow. Eventually the flow deposits lime mud and shale.

Pohler (1987) has reconstructed the bank and slope environments using evidence from the boulders. This is a bit like reconstructing the geological history of the Long Range Inlier by carefully examining the gneiss and granite boulders on the beach at Green Point.

The Cow Head Group is a vast and extraordinarily diverse paleontological store house that is still only partially explored. This is a consequence of the large number of different carbonate environments sampled in the conglomerates as well as the varied pelagic fossils in the shales.

Trilobites first described from Argentina rub cheeks with Australian graptolites, Nevadan brachiopods, Cordilleran conodonts, assorted carbonaceous microfossils and exotic (mainly undescribed) radiolaria and fish scales.

Note on the use of the term "Bed" in descriptions of the Cow Head Group

Kindle and Whittington (1958) gave the classic descriptions of the Cow Head Group. They subdivided the group into a series of units they called "Beds". These are not meant to be beds in the sedimentological sense, and most "Beds" are assemblages of many sedimentological beds. They are more akin to "Members" and "Formations" in the North American sense, except that the fossil content is an essential part of the definition. Some of the conglomerate "Beds", such as Bed 14, represent points in time. On the other hand, the predominantly shaley "Beds", such as Bed 13, represent millions of years.

Although this use of the term "Bed" is not sanctioned by the North American Stratigraphic Code, it is kept for the Cow Head Group as a descriptive device since it allows the precise stratigraphic assignment of an outcrop and has historic usage.

There is a parallel, but little used, legal system of nomenclature proposed for formal use in James and Stevens (1986).

The second day of our field trip will examine three key localities in the Cow Head Group, to illustrate the variations in sedimentary facies and to discuss the possible changes in the morphology of continental shelves over geologic time.

Stop 2-1
Table Point Ecological Reserve

This classic locality for Cambro-Ordovician sedimentary rocks is located just north of the community of Bellburns. The access road to Table Point is a small unmarked track on the west side of highway 430, about 2.1 km north of the bridge in Bellburns. The first few hundred feet of the road is rutted and may be flooded, but is passable with care in drier weather. Beyond this point, the road is narrow, but in reasonable condition. It eventually emerges into a flat gravel area where there are many branch tracks. Keep close to the shoreline to a point about 1 km from highway 430, and then walk west to shoreline outcrops.

> **Note that Table Point is a protected ecological reserve, intended to preserve rich fossil assemblages. *Collecting of any kind without a permit is strictly prohibited.* Keep an eye out for the angular cavities that mark where some of the best specimens were removed and transported to the Royal Ontario Museum just prior to establishment of the Ecological Reserve. These fossils now rub shoulders with some of the best Mistaken Point material.**

Table Point and adjacent areas are well-known geological sites, and there are many previous descriptions. The account that follows is modified and simplified from James *et al.* (1988). Most specialized field trips spend an entire day in this area, walking the extensive and complete shoreline section. Our field trip will visit only the uppermost part of the section, which includes part of the Table Head Group, and the overlying Goose Tickle Group. The sketch map of the locality in Figure 5 is the most recent work of Sheila Stenzel (Stenzel, 1992, Stenzel *et al.*, 1990).

The Table Point area exposes about 300 m of continuous stratigraphic shoreline section, including the upper part of the St. George Group, the St. George Unconformity, all of the Table Head Group, and the base of the overlying Goose Tickle Group. The latter represents easterly derived flysch, and is the autochthonous equivalent of the allochthonous green sandstones of the Lower Head Formation, visited at Lobster Cove Head on Day 1.

In its entirety, the Table Point area records a change in environment from tidal flats to deep basin, that occurred as the long-lived platform began to break up and founder during the initial stages of allochthon emplacement.

The Table Head Group is assigned to the Whiterock stage of the Middle Ordovician; rocks of this age are rare on the North American craton, where it appears to represent a hiatus in deposition. Carbonates of this age are only known around the periphery of the craton, notably here and in the Antelope Valley limestone of Nevada.

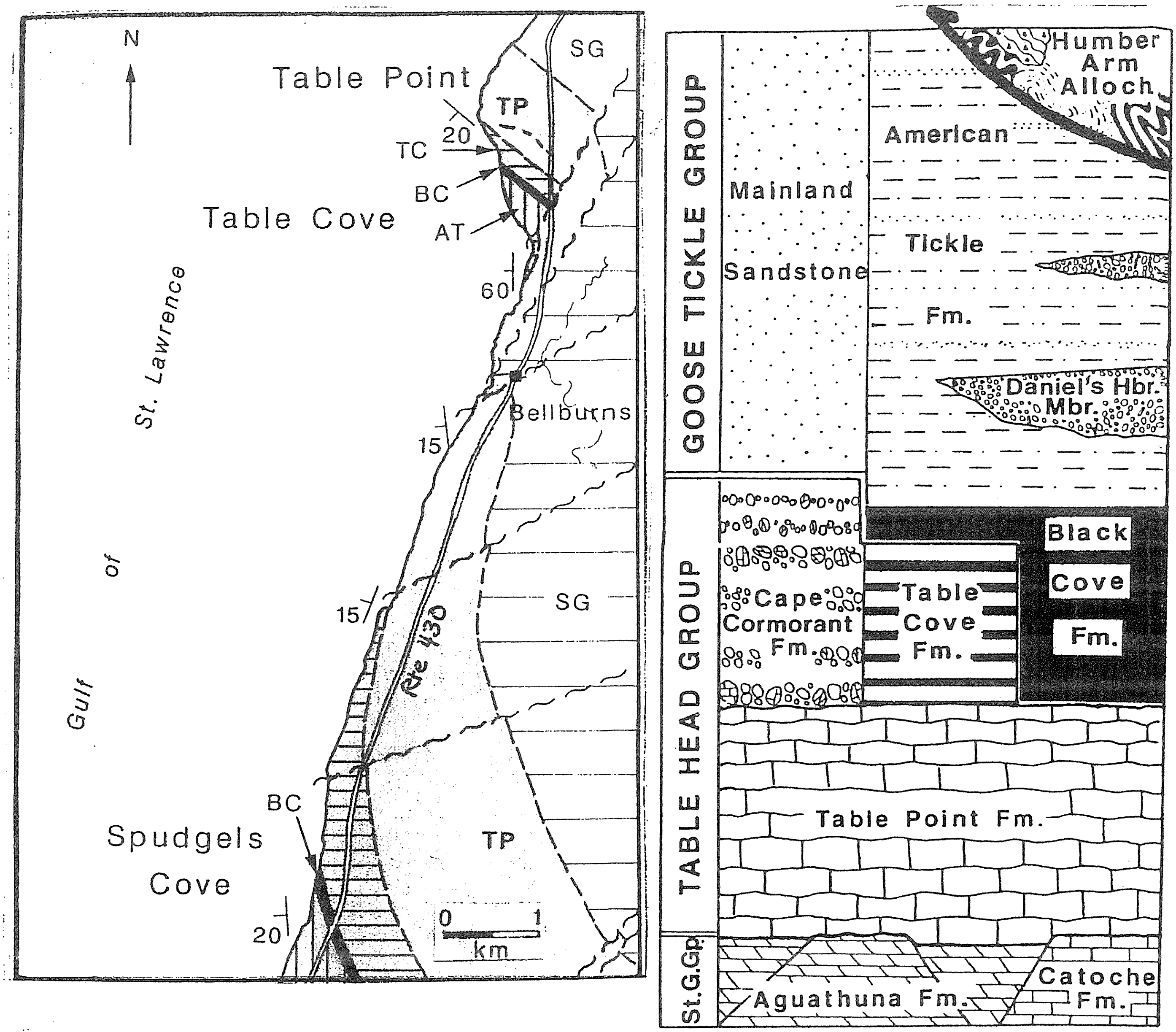


Figure 5. *Sketch of the Table Point area, from Stenzel* et al. *(1990). SG = St. George Group; TP = Table Point Formation; TC = Table Cove Formation; BC = Black Cove Formation; AT = American Tickle Formation.*

The description below applies only to the Table Head Group part of the section; for details of the St. George Group, *see* James *et al.* (1988).

The base of the Table Head Group is marked by the boundary between thick-bedded, massive dolostone of the St. George Group and a grey, burrowed, fossiliferous limestone.

The overlying dark-grey, rubbly weathering, limestones are monotonous and typical of much of the Table Point Formation, deposited in lagoonal to open subtidal environments as the platform subsided. An exceptionally fossiliferous bedding plane marks the bank margin facies and our visit starts here. It is interpreted to represent a shallow bank margin facies deposited just prior to block faulting and rapid drowning of the former platform. The bedding plane contains abundant sponges, bryozoa, pelmatozoa, orthid and strophemenid brachiopods, nautiloids, various gastropods and trilobites.

Above the fossiliferous horizon, there is a rapid transition into thin-bedded limestones and shales of the Table Cove Formation, representing a significant increase in water depths. Many beds in this part of the section show large- and small-scale slump structures and folding. The shale units become more abundant and thicker up section, and the Table Cove Formation eventually gives way to the black shales of the Black Cove Formation, visible only at low tide. During the deposition of the shales, the basin was starved of sediment derived from the shelf and from the advancing allochthons. This starved interval is known as a Bathyal Lull and is present in several analogous orogens just prior to the emplacement of allochthons.

Farther up section, the shales contain more and more green lithic sandstones representing the Goose Tickle Group. Paleocurrent directions and the presence of detrital chromite in these sandstones and the coarsening upwards sequence indicate a source in the advancing thrust sheets now within the Humber Arm Allochthon.

Stop 2-2
The Arches Provincial Park

These well-known outcrops are at "The Arches Provincial Park", clearly signposted from highway 430 in both directions. The Arches are an impressive erosional feature developed within a limestone conglomerate of uncertain affinity – it is not known if these rocks are autochthonous (i.e., conglomerates of the Daniels Harbour Member, Goose Tickle Group) or allochthonous like the classic conglomerates at Cow Head (*see* the next stop and Figure 6). Outcrops north of the Arches resemble the Goose Tickle Formation, suggesting the first alternative, and this is strengthened by a dolomitized calcarenite that overlies the conglomerate at the Arches. A similar conglomerate–calcarenite association occurs in coastal outcrops of the Daniels Harbour Member just northwest of the river mouth of Portland Creek.

Dolomitization of the conglomerate has led to porosity development, and the rock contains traces of natural gas, which gives a characteristic smell of sour gas when broken. Rocks like this could well be oil-bearing at depth.

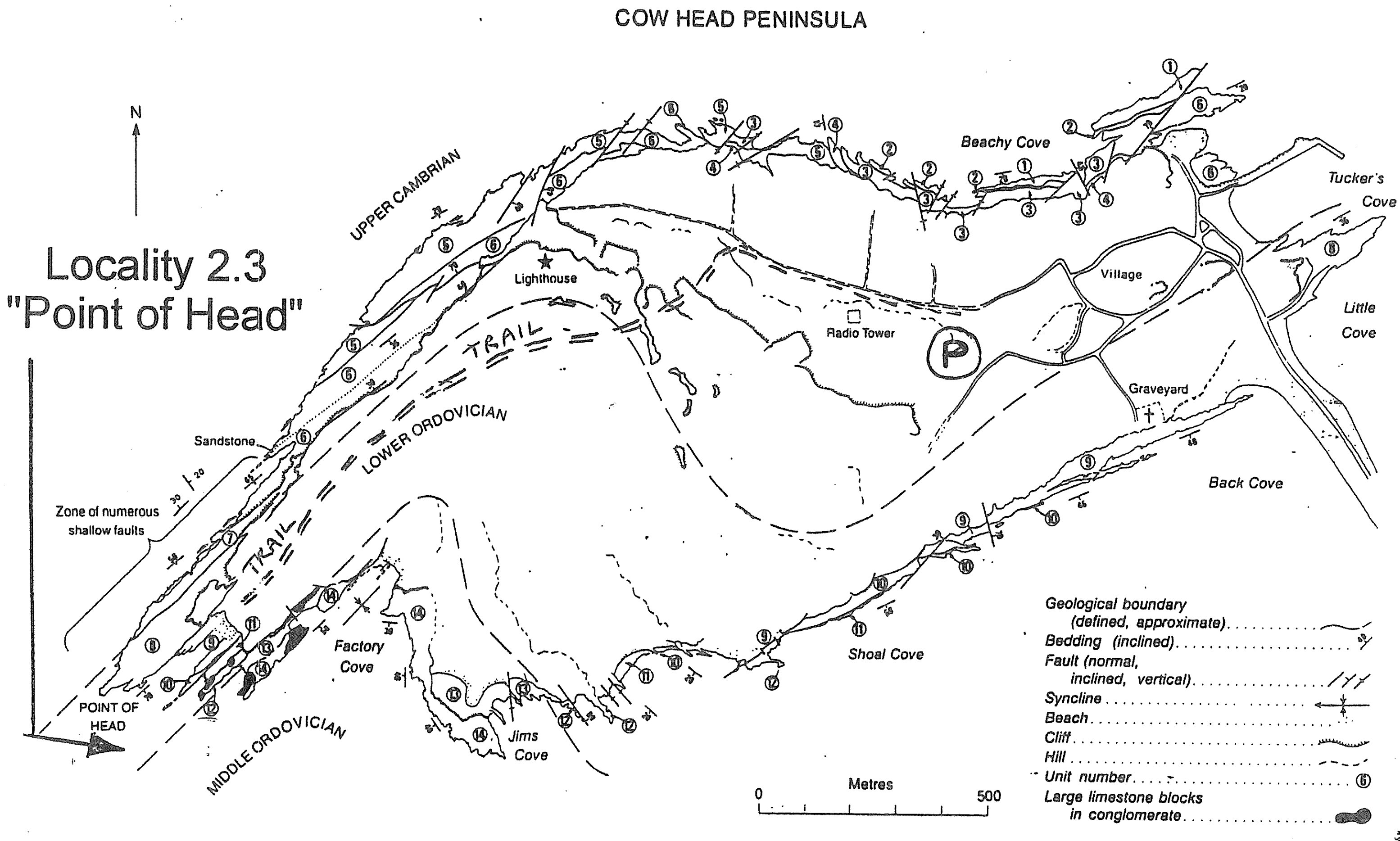


Figure 6. *Geological map of the Cow Head Peninsula, showing the area visited on this trip. Other numbers refer to a previous field trip of more detailed character. From James* et al. *(1988).*

The arches themselves are generally considered to result from recent marine erosion; it is also possible that they could be part of an exhumed freshwater-cut subterranean karst drainage system developed when sea level was lower than today.

Stop 2-3
Cow Head Group at the Type Locality

The Cow Head Peninsula, attached to "the mainland" by a gravel isthmus, is an internationally famous geological locality. This trip will visit only a small part of the peninsula but it includes rocks from Upper Cambrian to early Middle Ordovician age. The outcrops are located at the southwestern tip of the Peninsula and comprise a dip section. Both the south and north shores are essentially strike sections.

Drive into the community of Cow Head and turn onto "Pond Road", which leads across the isthmus. Turn left on the dirt road that leads towards the communications tower, past the cemetery, past several limestone outcrops that contain recent mollusc (*Hiatella arctica*) borings that record falling Holocene sea level and park in the open area below the Gros Morne Theater stage. Walk a short distance north, then follow an old road downhill. Take the signposted trail for the lighthouse and keep going to the branch trail labelled "Point of Head". Follow this trail through thick tuckamore until it emerges at the southeast tip of the peninsula (20-25 minutes walk in total).

Note that the Point of Head part of the trail has a very well-worn aspect. In 1964, the trail had a similar well-worn look, but was not passable because of thick bush. The trail has only recently been cleared as part of tourism initiatives. Given the long archaeological record (4500 years) of settlement of the peninsula and the lack of historic settlement at the Point of Head, it seems probable that the trail has had a long history of use, perhaps serving many successive cultures.

On the way to the point, look out for the rock overhang (shelter?) with its calcium bicarbonate-rich drips on the left-hand side of the trail, about two-thirds of the way to the point.

There are numerous previous descriptions of the Cow Head Peninsula (James and Stevens, 1986). The following description is adapted and simplified from James *et al.* (1988). For a more complete description, including other parts of the peninsula, *see* James and Stevens (1986). The overall stratigraphy of the Cow Head Group and the various types of limestone conglomerate that it contains are illustrated in Figures 6 and 7 (from James *et al.*, 1988).

In general, limestone conglomerates in the northern part of the section are of Cambrian age. Many of the beds contain wind-blown sand. Some of the sand retains a red hematitic coat suggesting that it was blown out to sea directly from a desert bypassing the river and beach environments. Other beds contain large boulders of white limestone, and cut down some 4 m into the underlying strata. The actual point is formed by lowermost Ordovician limestone conglomerate. The cove southeast of the point (our stop) is formed by a sequence of thin-bedded shales, limestones and thick debris flows which are equivalent in age to the autochthonous St. George Group and lower parts of the Table Head Group. The conglomerates contain a wide variety of limestone clasts, with some large ones approaching 4 m in size.

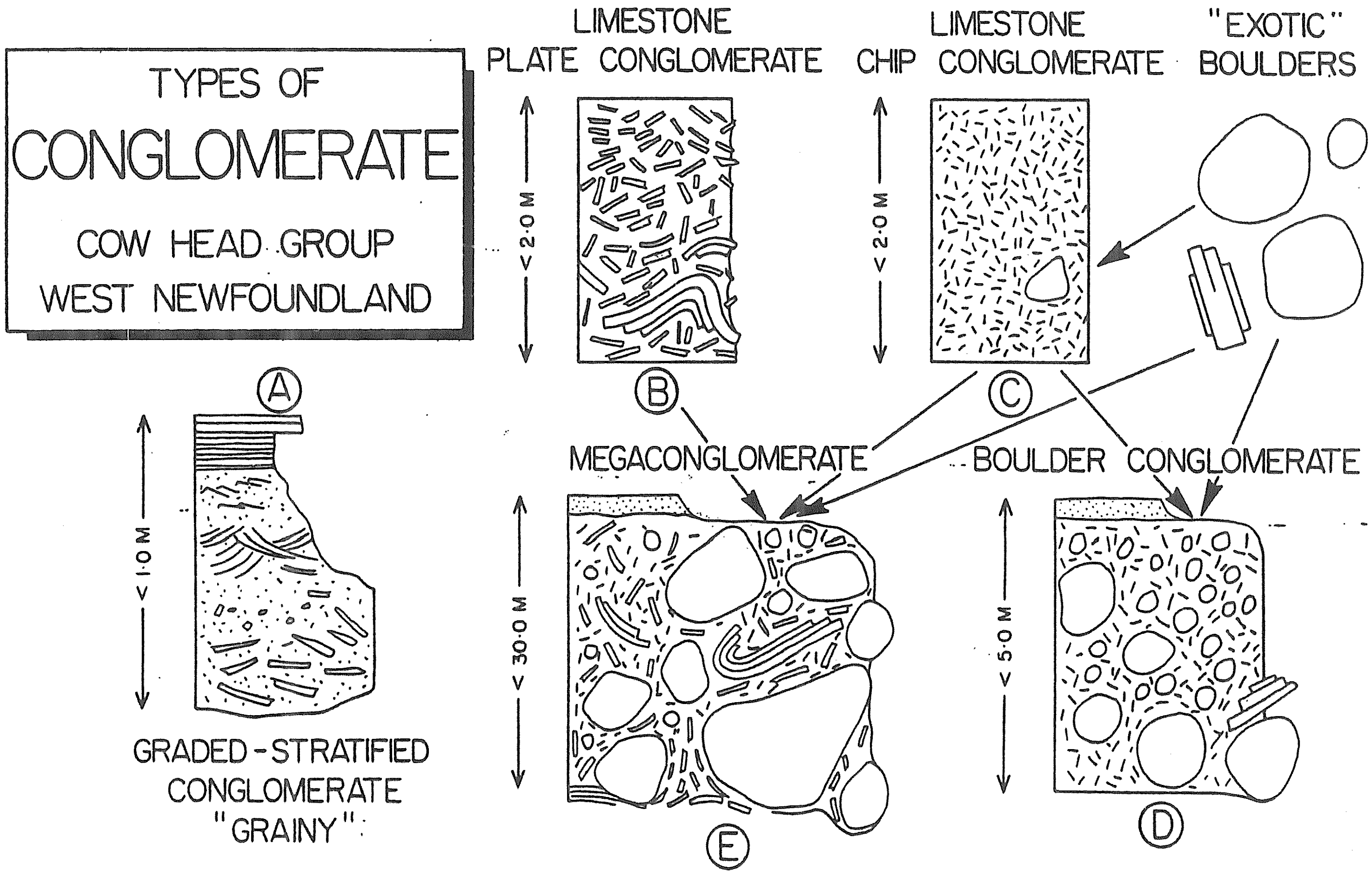


Figure 7. *The different types of conglomerate facies recognized in the Cow Head area. From James* et al. *(1988), after Hiscott and James (1985).*

The top of some of the conglomerates is marked by a calcarenite cap representing the settling of finer material. In contrast, the top of Bed 10 is erosional. Large boulders in the upper part appear to have been planed off prior to deposition of the next unit, but the mechanism for this is unclear.

This debris flow is followed by another series of shales and thin-bedded limestones of Early Ordovician age. This part of the section contains several brown-weathering dolomitic units – perhaps precipitates from upwelling deep, anoxic waters or dolomitic turbidites swept into deep water by erosion of dolomitic tidal flat shelf carbonates of the topmost unit of the coeval St. George Group.

There is a wide variety of clast types in the conglomerates, with an equally wide variation in the degree of early diagenesis. Many blocks are fossiliferous, and contain trilobites, brachiopods, gastropods and sponges. Some blocks clearly contain internal bedding, now at variable angles, and there are also blocks of previously formed conglomerate and brown siltstones akin to those in the underlying beds.

Green sandstones of the Lower Head Formation above Bed 14 can be see at the lowest tides or by diving.

Graptolites occur in the shales and can be correlated with the standard Australian and New Zealand graptolite zones. It should be noted that the eight or nine Lower and Middle Ordovician graptolite zones you take in at a glance at the Point of Head are thousands of metres thick in the standard regions.

Radiolaria occur in the interbedded limestones. They can be isolated by acid treatment and one day, Cow Head will be an important international radiolarian reference section for rocks of Lower Paleozoic age.

Note that our stop is in the Ordovician part of the succession characterized by discrete megaconglomerate containing interbedded shale and limestone. Time does not permit a stop in the contrasting Cambrian part of the sequence with its higher proportion of conglomerate but lesser variety of clasts.

It would appear that during the Cambrian, after the extinction of the Lower Cambrian Archeocyathids, there were no organisms capable of maintaining a reef-like rim to the carbonate bank. The bank edge was more like a ramp with no abrupt change of slope. Relatively minor disturbances such as storms or small, passive margin earthquakes could trigger numerous small debris flows.

By the Lower Ordovician, various organisms had evolved that, together, could maintain a reef-like rim to the carbonate bank. These ranged from calcareous algae to foraminifera, stromatoporids, bryozoa and sponges. Corals were not common in western Newfoundland until later in the Ordovician. With a self sustaining rim, only massive triggers such as major near-trench earthquakes, major sea level fall or close bolide impacts caused rim failure and start debris flows. Examples of the rim facies are found in the megaconglomerates.

Stop 2-4
Martin Point Section

These outcrops of the Cow Head Group are located 7.6 km south of the bridge across Western Brook, near the "S. S. Ethie" viewpoint in Gros Morne National Park. A steep dirt track provides access to fishing shacks and shoreline outcrops located on and around the point.

The Martin Point Section consists of sedimentary rocks that are intermediate in character between the proximal conglomerates of Cow Head and the distal shale–limestone sequence at Green Point (*see* the next stop). The following description is adapted and simplified from James *et al.* (1988). The cliffs east of the point expose chip, plate and boulder conglomerates that resemble those of the Cow Head area. These pass upwards into green-grey shales, siltstone, and thin-bedded limestone of the Upper Cambrian Martin Point Member. The Lower Ordovician Broom Point Member is a series of thin-bedded limestones, which contains prominent boulder conglomerates towards the top. These are overlain by reddish shales, considered to have formed under oxidizing conditions below a postulated oxygen minimum layer. About 750 m south of the Point, these are overlain by green sandstones of the Lower Head Formation.

Stop 2-5
The Green Point Cambrian–Ordovician Stratotype Boundary

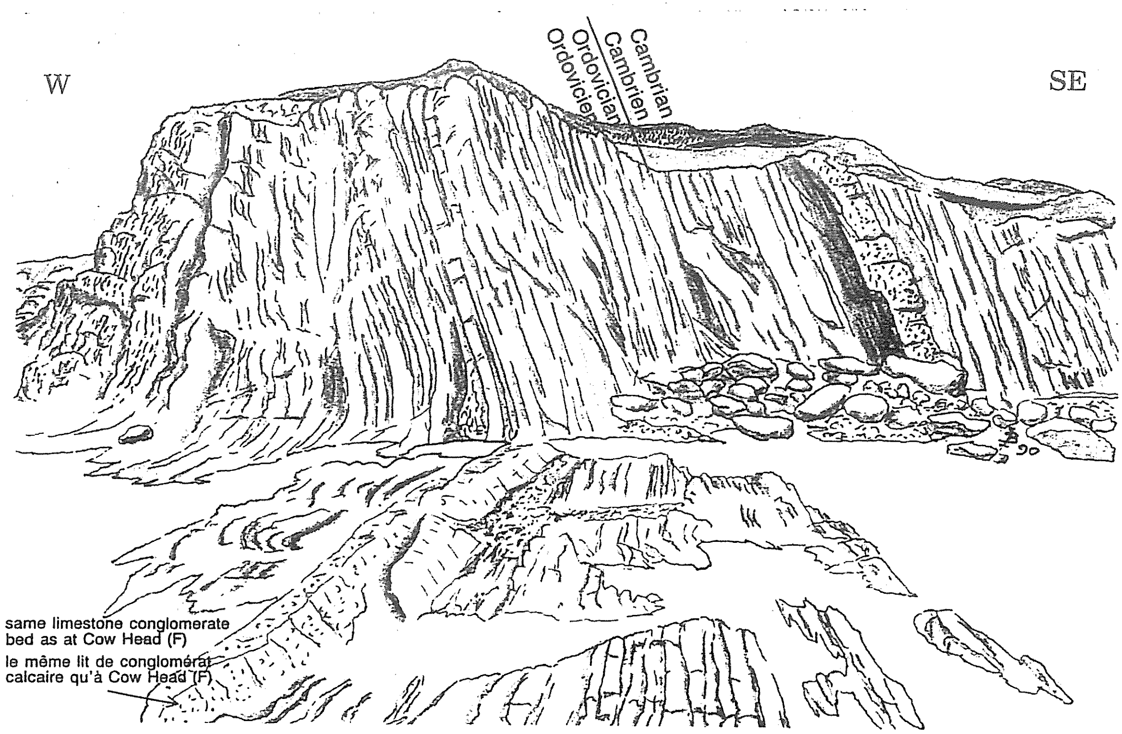
Our stop is located just north of the signposted Green Point camping area in Gros Morne National Park. Turn west on a small dirt road about 200 m north of the campground access road. This leads down to the shoreline and fishing shacks, but the last section is steep and rough and is not recommended for low-clearance vehicles. It may be prudent to park at the top of the hill and walk. The outcrops are located northwest of the fishing shacks and are best seen at low tide.

The following description of the Green Point locality is adapted and simplified from James and Stevens (1986) and James *et al.* (1988). The profile sketch of the location (Figure 8) is taken from Berger *et al.* (1992). Note that the outcrops are overturned and dipping southeastward but are younging to the northwest.

This is a deep-water, distal facies of the Cow Head Group, and contrasts with the more proximal facies represented by the limestone conglomerates of the type locality. Significant limestone conglomerates are confined to near the Cambro-Ordovician boundary, that is, rocks equivalent in age to the major conglomerates at the Point of Head at Cow Head.

The lowermost strata are shales, limestones, siltstone turbidites (commonly rippled and cross-laminated), thin lime mudstones, lenticular carbonate conglomerates showing clast imbrication and rare sandstones. Up section, dark green shale is predominant, and alternates with thin limestones of both pelagic and turbidite origin.

North of the Point, a surprising amount of outcrop occurs between the erratic boulders below high tide.



H Green Point (from the intertidal platform at low tide)

The cliff and the intertidal platform expose interbedded limestone conglomerate and shale (7). The beds are overturned, so that the youngest is to the left. The thin-bedded rocks were deposited in deep water by turbidity flows of limestone-sand-mud mixtures from shallower depths. The graded bedding, crossbedding, and basal scour marks common in these rocks were produced by the flow process. One of the thicker conglomerate beds is the deepwater equivalent of the boulder bed at Cow Head (F). This exposure has been proposed as the global standard for the boundary between the Cambrian and Ordovician rocks because of sharp changes in microfossils.

Between high and low tide levels, the rock has been planed off horizontally, largely by frost action which is so frequent during most of the year. During low tide, the rock is broken up by water freezing in the cracks, then washed away by waves during high tide. Erratic boulders from the Long Range have dropped onto the platform as the cliff was cut back into the overlying till and iceberg sediment. Their attached barnacles and mussels show that some boulders can resist movement by winter pack ice.

H Green Point (depuis la plate-forme intertidale à marée basse)

Le calcaire, le conglomérat et le shale (7) interstratifiés sont mis à nu dans la falaise et sur la plate-forme intertidale. Les couches sont renversées de sorte que la plus récente se trouve à gauche. Les roches finement stratifiées ont été mises en place en eau profonde par des coulées de turbidité composées de mélanges de calcaire, de sable et de boue provenant de zones de plus faibles profondeurs. Le granoclassement, la stratification oblique et des cicatrices d'affouillement basales que l'on remarque fréquemment dans ces roches, doivent leur formation à ces coulées. Une des couches plus épaisses de conglomérat est l'équivalent en eau profonde de la couche de blocs observée à Cow Head (F). Cet affleurement a été proposé comme reférence à l'échelle du globe de la limite entre les roches du Cambrien et de l'Ordovicien en raison des changements très nets observés dans les microfossiles.

Entre les niveaux de marée haute et de marée basse, la roche a été aplanie à l'horizontale surtout suite à l'action du gel tellement fréquent pendant la plus grande partie de l'année. À marée basse, la roche est fragmentée lorsque l'eau gèle dans les fissures et les fragments sont emportés par les vagues à marée haute. Des blocs erratiques provenant des monts Long Range ont été abandonnés sur la plate-forme à mesure que reculait la falaise dans le till sus-jacent et les sédiments laissés par les icebergs. Les balanes et les moules qui leur sont fixés indiquent que certains blocs ne peuvent être déplacés par la banquise en hiver.

Figure 8. *Sketch of the Green Point locality, and location of the Cambrian–Ordovician boundary. Original drawing and bilingual caption from Berger* et al. *(1992). The original drawing was by Ian Brookes.*

Just south of the Point, thin limestones display peculiar dome-and-basin folding or wrinkling, and have in some cases become broken and contorted. How these features formed is not understood; suggested origins include slumping to compaction deformation to expansive recrystallization. The most spectacular wrinkled bed lies near the Cambrian–Ordovician boundary.

In the summer of 2000, the International Stratigraphic Committee, with the approval of the International Union of Geological Sciences (IUGS), designated Green Point as the global stratotype for the Cambrian–Ordovician boundary. The boundary is actually defined by the first appearance of the conodont *Iapetognathus fluctivagus* (which is unfortunately, hard to see without a microscope), but also coincides roughly with the appearance of the earliest planktonic, siculate graptolites that traditionally have marked the base of the Ordovician.

The official boundary itself is not marked with a golden spike in the field, but lies in the shales between the wrinkled unit and the first limestone conglomerate bed (*see below*). It is a little different from the boundary shown by James and Stevens (1986) due to a change in the definition of the boundary.

A fault affects the boundary in the cliff section, but the boundary is unfaulted in the foreshore.

Newfoundland, therefore, is the official home of the base and the top of the Cambrian System but its heart remains in the mountains of Wales.

DAY THREE – ALLOCHTHONOUS SUBMARINE CHANNELS, THE BAY OF ISLANDS OPHIOLITE AND TROUT RIVER SEA LEVEL CHANGE

Leaders: Tom Calon, Robert K. Stevens and Rob Hingston

Overview

Day three of the field trip will visit a mixed bag of rocks, from mantle lherzolites to glacial sand. In the morning, we will travel by road to the south side of Bonne Bay, passing some of the outcrops visited on Day 1. We will visit spectacular siliciclastic and conglomeratic units within the Humber Arm Allochthon, which record the erosion of both autochthonous platformal rocks and their basement. After a brief stop on the Ordovician sea floor, we will descend into the mantle. To be more precise, most of us will actually ascend to the mantle by hiking into the Tablelands Ophiolite. A smaller group of non-hikers will take the optional boat excursion (weather permitting) on Trout River Pond, and will visit some shoreline outcrops, including the metamorphic aureole of the ophiolites. Our final stops will be a visit to interesting postglacial features and panoramic views around Trout River. The day will conclude with a relaxing boat trip across Bonne Bay to the Marine Station at Norris Point.

Stop 3-1
Channelled Conglomerates of the Meadows Formation
WARNING! WATCH FOR TRAFFIC!

Our stop is located along highway 431, 21.1 km from the Route 430/431 junction in Wiltondale. A long downhill roadcut provides spectacular exposures. An earlier outcrop (15.8 km from the Route 430/431 junction) of buff and white limestones marks the western limit of autochthonous platformal outcrops. The low country between this outcrop and the present stop is mostly underlain by the Goose Tickle Group and mélange.

The Meadows Formation is part of a slice of Lower to early Middle Cambrian clastic sedimentary rocks within the Humber Arm Allochthon. These are time-equivalent to the Cambrian platformal sediments (Hawke Bay Formation) seen on Day 1. The outcrop shows lower quartzose turbidites, shales and siltstones, with interbedded spectacular channelled conglomerates.

There is a variety of clasts, but the clast population is dominated by rocks from the equivalent platformal sequence, i.e., the Hawke Bay Formation and the older Forteau Formation, including arkose, quartzite, and fossiliferous limestone along with semi-lithified clasts of limestone and shales. Fossils in the limestone clasts include the trilobite *Bonnia* and the conical mollusc *Salterella*. There are also mafic volcanic clasts (rift facies volcanics?) and boulders of basement gneiss and granite.

These rocks represent a late Lower Cambrian period of low sea level, when the platformal assemblage was exposed to erosion. Quartz sand from the Canadian Shield prograded across the shelf and deep canyons were cut into the continental rise, funnelling submarine conglomeratic debris flows into the continental rise prism. Until recently, no early Middle Cambrian fossils were known from the platformal rocks surrounding Iapetus (Palmer and James, 1979). However, recent work on mixed carbonates and siliciclastic rocks of the Bridge Cove Member, Hawke Bay Formation, on clastic rocks only in Gros Morne, and on Port au Port Peninsula have recovered trilobites and other organisms of Middle Cambrian age from the upper part of the Hawke Bay Formation, in contrast to only Early Cambrian fossils in the Lower part of the same formation (Knight and Boyce, 1987, Knight and Boyce, unpublished data, 1998, 1999, in preparation).

Although it is probable that the basement directly supplied the plutonic clasts, it is possible that the clasts were reworked from early rift conglomerates such as the Bateau Formation of Belle Isle (Williams and Stevens, 1969).

Equivalent conglomerates occur at Bakers Brook Falls, along on of the park trails near Rocky Harbour, and, a little more accessibly, behind the Bank of Montreal in Corner Brook, where archeocyathid-bearing boulders can be found. Similar conglomerates have also been found recently in outcrops north of Georges Lake, southwest of Corner Brook.

Stop 3-2
Panoramic Views of Bonne Bay and the Tablelands Ophiolite

This stop is located at the viewpoint just east of Woody Point, and is largely a photo opportunity. Most elements of the Park geology can be seen from here.

The view of the Tablelands looming over Bonne Bay is justly famous, as is the excellent view of the conical "Pica (Peak) of Tenerife", formed by the amphibolitic dynamothermal aureole of the ophiolite.

"Gibraltar Peak", the flat-topped mountain across the bay, was also named by Captain James Cook. It resembles the famous fortress. It is made up, in part, of transported volcanic rocks of rift origin from the late Precambrian part of Summerside Formation. All of the east shore of East Arm is formed by greywackes of the Summerside Formation.

East Arm itself is cut into a mélange zone, remnants of which can be seen all along the west shore of the Arm. It cuts out most of the upper part of the Humber Arm Supergroup in this area.

Gros Morne is also visible from here, as are the far peaks on the Long Range peneplain.

WARNING! WATCH FOR TRAFFIC!

The deformed gabbro on the far side of the road belongs to the upper part of an ophiolitic unit within the Little Port Complex. We will see the upper part of this slice at the next stop.

Stop 3-3

Ocean Floor of the Little Port Complex and a discussion of serpentinization of Table Mountain and its products.

WARNING! WATCH FOR TRAFFIC!

This outcrop is located at the first viewpoint on the road towards Trout River. It is an extensive (but altered) outcrop dominated by pillow lava, pillow breccia, chert and red shales. No fossils have yet been found in these shales though there are possible radiolarian remnants.

The prominent rusty zone in the centre of the outcrop provides evidence of hydrothermal alteration and sulphide deposition, and probably represents a part of the plumbing of a small submarine hydrothermal system.

The outcrop is interpreted as the upper part of an ophiolitic basement to an island arc system, which together make up the Little Port Complex. Gabbros of this ophiolite were seen at the previous stop and the sheeted dyke unit is exposed in the road cut just west of the Discovery Centre. The dykes strike nearly parallel to the road and contain small patches of late granophyric differentiate.

A note on serpentinization and other alteration features of the mantle sequence

The stream directly in front (south-southwest) of the lookout is the headwater of Wallace Brook. Most of its water comes from acidic bogs on top of Table Mountain and melting snow in the cirque.

In contrast, the first rock canyon above the road is the site of some of the most alkaline seeps on earth. Water issues from the seeps with a pH of 12. Furthermore, tiny bubbles of methane and even hydrogen have been detected in the seep. About 50 years ago, Brinex drilled an EM anomaly and intersected a massive graphite vein in a serpentine zone (The tracks left by Brinex are still visible on both sides of the stream!).

All of these observations can be explained as the result of an ongoing serpentinization of mantle lherzolites due to an interaction with groundwater at ambient temperatures. Two separate phenomena are at work, one produces alkaline waters in lherzolitic areas and the other produces strongly reducing conditions in all ultramafic areas.

Both processes can act because glaciation and intense modern physical weathering have left large areas of fresh ultramafic rock exposed at the surface and because the fresh mantle minerals are highly out of equilibrium with near-surface conditions. Furthermore, the melting of the glaciers has left the flanks of Table Mountain unsupported and in a state of tension. Consequently, internal fissures, which are probably kept open by the surficial freeze/thaw cycle, formed that allow fluids access into the ultramafic rock where alteration can continue.

Hyperalkalinity is a result of the fact that the serpentine minerals cannot accommodate the calcium released during the alteration of diopside. The calcium is released into the groundwater as calcium hydroxide, which substantially increases the alkalinity.

On exposure to the atmosphere, carbon dioxide is immediately adsorbed and a banded calcite tufa precipitates. The seeps are home to archeobacteria that thrive in these hyperalkaline conditions and these may influence the precipitation process. A similar process operating in the marine environment produces the newly discovered white smokers.

Eventually the seeps seal themselves due to surface plugging by calcite and about a 10% expansion of the rock at depth due to serpentinization. New seeps form elsewhere. The pale patches of rock scattered around Table Mountain are fossil seeps.

A little of the calcite around these fossil seeps has reacted with the normal magnesium-rich surface water to form extremely unusual terrestrial dolomite.

It should be noted that much of the scree on Table Mountain is cemented by calcite and that it is potentially datable by radiocarbon methods because it formed by adsorbing atmospheric carbon dioxide just like any tree. An interesting postglacial chronology could be obtained, especially since the calcite almost certainly contains occluded pollen grains.

Serpentinization also produces highly reducing environments mainly because of the change from ferrous to ferric iron during the reaction. This can lead to the reduction of water to hydrogen and any dissolved carbon dioxide can be reduced to graphite and even methane and ethane. This reaction may well lead to accumulations of inorganic natural gas in certain environments.

After a geologically short time, all of the accessible fresh mantle rock both on the surface and at depth is hydrated and the unaltered mantle rock is safely sealed in a protective serpentine skin until the next glaciation or tectonic disturbance. It is this serpentine seal together with a sedimentary cover (Carboniferous?) and a stable tectonic environment that has led to the survival of original Lower Ordovician mantle mineralogy for nearly half a billion years.

Acadian? Calcium metasomatism led to the formation of the rare mineral calcic Xenotolite along Winterhouse Brook.

Similar calcium metasomatism during the emplacement of the Hare Bay Allochthon led to the formation of nephrite jade deposits.

Stop 3-4A
Hiking to the Moho and Beyond

This consists of a hiking excursion into the Tablelands, and several discrete stops of interest. **Details will be provided separately.**

Stop 3-4B
Boat Trip along the Trout River Ponds

For those who, for one reason or another, cannot scale Table Mountain, there is a boat trip along the Trout River Ponds through the Bay of Islands Ophiolite. Depending on wind conditions, this may or may not be more relaxing than the hike. Numbers are limited!

Landing on the rocky outcrops can be very dangerous and should only be attempted in the calmest of weather. Do not be disappointed if we do not attempt to land. Bring binoculars if possible.

The trip features good views of the mantle and cumulate sequences of the Table Mountain Massif as well as views of most parts of the North Arm Mountain ophiolitic massif, including the basal metamorphic slab.

Overview of the Bay of Islands Ophiolite

Early workers regarded the Bay of Islands Igneous Complex as a group of Devonian igneous intrusions emplaced into the Humber Arm Supergroup sediments. The first debates concerned the shape of the intrusions; i.e., were they laccoliths or lopoliths? Cooper (1936) and Smith (1958) provided the classic descriptions of the rocks. Both regarded the rocks as *in situ* intrusions.

Kay (1951) noted the dilemma of eugeosynclinal rocks with their typical mafic/ultramafic association, resting above miogeosynclinal rocks and concluded that western Newfoundland provided a rare example of a miogeosyncline turning into a eugeosyncline.

Rodgers and Neale (1963) assumed that the igneous rocks were intruded into the Humber Arm sediments and were transported along with them.

Stevens (1967) first recognized the igneous rocks as ophiolites, thus making the Bay of Islands Igneous Complex the first ophiolite to be recognized in North America. The recognition resulted from the discovery of detrital chromite from the ophiolites in the underlying Humber Arm sediments, showing that they were not intruded into the sediments. The recognition of sheeted dykes near York Harbour, west of Corner Brook clinched the matter. Sheeted dykes are typical of ophiolite sequences and had also been described from drilling of the ocean basins.

All subsequent workers have accepted this interpretation but there has been considerable debate on the origins of the ophiolite suite. All agree, however, on an extra-continental origin.

Stevens (1970) first suggested that the Bay of Islands Ophiolite represented Oceanic crust and mantle, a view elaborated by Church and Stevens (1971, *see* Anon, 1971, for discussion).

The importance of the Bay of Islands Complex is twofold: a) It provides critical information on the evolution of the Northern Appalachians as a continental margin and b) it provides more general information on the formation and evolution of extra-continental crust and upper mantle. For example, Church and Stevens (1971) showed that it was possible to examine the Lower Paleozoic Oceanic Moho in much greater detail than the present day equivalent. Figure 9 gives a generalized section through an idealized ophiolite.

Boat Trip Itinerary

The trip leaves from Tour Boat dock on the north side of Lower Trout River Pond. All of the low ground between Table Mountain and the coastal hills to the west is underlain by a mélange that separates the ophiolite from the Little Port Complex. More resistant blocks (knockers) within the

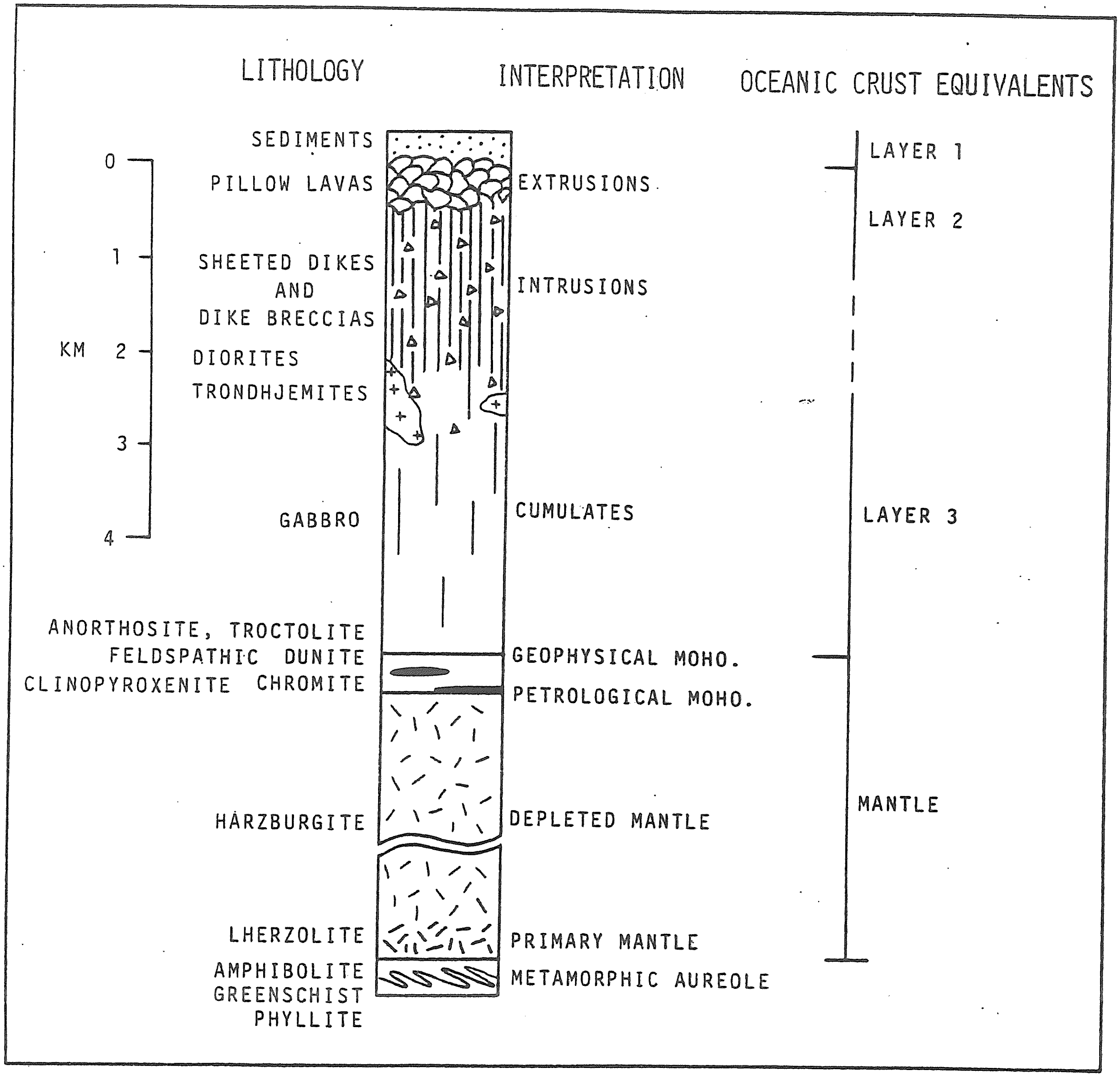


Figure 9. *Diagrammatic section through the Bay of Islands ophiolite complex, showing equivalent layers in the modern oceanic crust. From Williams and Malpas (1972).*

mélange form the isolated hills. Most are blocks of pillow lava of uncertain affinity. They could be derived from the ophiolites, from the Little Port Complex, from the Skinner Cove Volcanics or from some other source, perhaps in the Humber Arm, which provides the mélange matrix. The blocks have not been studied in any detail.

Looking north at the Table Mountain Massif, there are good views of the gabbro/ultramafic contact, i.e., the Paleozoic Moho. Note the massive xenoliths of peridotite in the gabbro and the large blocks of gabbro that have slid from the higher, sagging, gabbro scarp since the last glaciation.

Miners Point, at the narrows between the two ponds, is not a recent slide block but a faulted slice, possibly from the North Arm Massif to the south. Here the gabbro/peridotite contact is at lake level. The northern bounding fault probably intersects the southern shore of the lake at Rubble Brook.

Once through the Narrows, there are views of the mantle peridotites of Table Mountain to the north and the sheer cliff (0.5 km/1650 ft high) of sheeted dykes and basalt of the North Arm Massif to the south.

Note the paler patches scattered throughout the Table Mountain peridotites. These are calcite spring deposits, as previously described at Stop 3.3. Many of the scree slopes are cemented and stabilized with calcite within a metre of the surface.

Plant life is scarce on Table Mountain because of toxins such as nickel and chromium in the rocks and a lack of essential elements such as potassium and phosphorous. These chemical characteristics combined with harsh climatic conditions inhibit plant growth to such an extent that the Common Juniper reaches a diameter of only a few centimetres after 300 years of growth and is blasted by the wind to a near-horizontal position. A Snowshoe Hare could easily jump over these oldest know living trees in the province! The annual growth rings are frequently less than millimetre wide.

It is hard to distinguish individual dikes in the sheeted dike complex along the south shore of the lake, especially in overcast weather. This is because the dikes strike nearly parallel with the shore. To get the best view, you must look obliquely eastwards along the cliff. Rare patches of pillow lava occur as screens between the dikes.

A major reverse fault at Rubble Brook brings gabbro into contact with the basal brownish lherzolite (olivine–diopside–enstatite rock). All of the cumulate peridotite (dunite) and most of the depleted mantle peridotites (hartzburgite) are cut out. It is entirely possible that the rocks under the fault belong to the Table Mountain Massif rather than the North Arm Mountain Massif. The fault is thought to continue under the lake and surface again along the north flank of Miners Point.

Rubbly gabbro blocks have slowly slid from the gabbro scarp west of the fault. Large postglacial sag-related fractures cut the gabbro and these allow the detachment of the gabbro blocks that give Rubble Brook its name. It is not known if the blocks are still moving or if they are stabilized by calcite cement.

A small headland about two kilometres east of Rubble Brook exposes the best cross section of the basal metamorphic slab of the ophiolite in the Park. Here black garnet–amphibolites are in sharp contact with a banded garnet peridotite. The amphibolites grade into greenschist and eventually pillow lava away from the contact. The amphibolites formed between 720-850° centigrade and at 7-12 Kbar. Locally the amphibolites are partially melted to yield a liquid of quartz–albite (i.e., trondhjemitic) composition.

Elsewhere, the amphibolites preserve xenoclasts of their protolith, pillow basalts and gabbro, perhaps the upper parts of an ophiolite.

Argon/argon dating yields an age between 436 and 469 Ma for the formation of the amphibolites, which is at least 17 Ma younger than the 486 Ma age of the ophiolite (Dunning and Krough, 1985).

The amphibolite represents the earliest record of movement during the assembly of the Humber Arm Allochthon.

The plate tectonic interpretation of these relationships will be discussed during the return trip, weather and engine noise permitting.

Stop 3-5
Viewpoint near the Trout River Campground

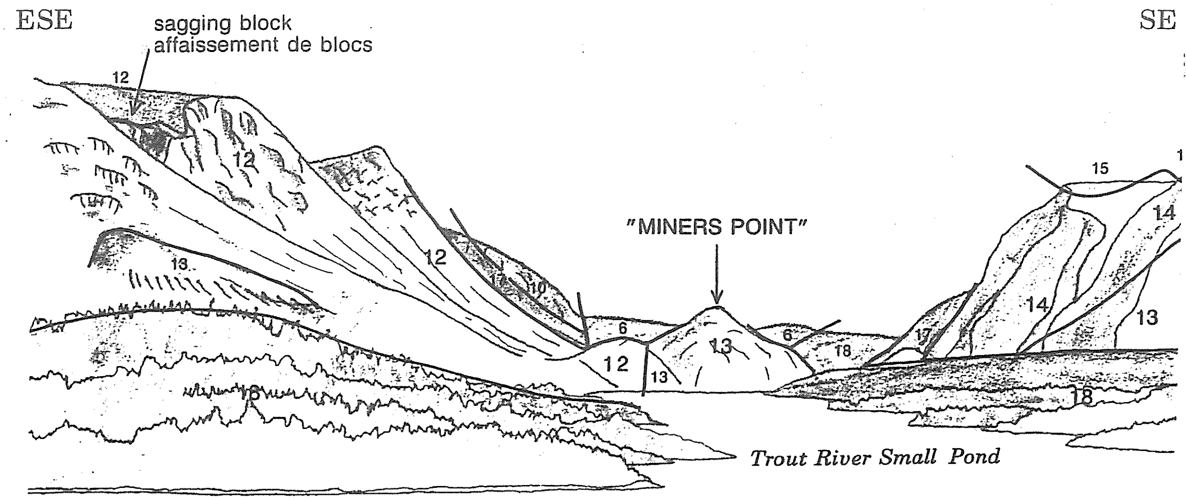
Hikers and boaters will eventually reconvene at this stop.

From the community of Trout River, continue west along the shore of Trout River, and follow the signs for the campground. Turn right a short distance after the narrow bridge, and ascend to the viewpoint.

This is another of Gros Morne's more spectacular views, and it contains a wealth of geological information. It is depicted in Figure 10, from Berger *et al.* (1992). The south side of the Tablelands Ophiolite is clearly visible, and the contrast between red-weathering ultramafic rocks and grey-weathering gabbro is obvious. Miner's Point, at the head of the lake, also consists of gabbro. A large detached piece of gabbro has moved towards the lake in postglacial times. A vertical fault occupies the lake valley, and the hills to the south are part of the North Arm Mountain massif. This ophiolite is dropped "down" relative to the Tablelands and tilted towards you, exposing the metamorphic aureole at the far end of the lake. The high peak in the south is Mount St. Gregory (674 m a.s.l.), also one of the highest points on the Island.

Stop 3-6
Sea Level Changes, Trout River

The community of Trout River is built on and around a large terrace of gravel and sand that separates the glacially carved valley of Trout River Pond from the sea. This terrace is a classic ice-marginal marine delta, deposited in the sea by meltwater flowing west from a glacier that existed



R View up Trout River Small Pond (from lookout)

The glacially oversteepened cliffs on the right are held up by strong gabbro (**13**), sheeted dykes (**14**), and pillow basalt (**15**). On the left, the distant yellow-brown slopes of the Tablelands are composed of peridotite (**12**). The nearer Tablelands slope is stepped with old sagged and slumped blocks, one of which is a large gabbro mass, and there are patches of brown peridotite till dragged down-valley by the glacier. The wooded foreground on both sides of the pond, as well as the lowland on the far right, is underlain by the easily-eroded mélange (**18**).

The valley was initiated by river erosion along steep faults in preglacial time after the Tablelands plateau was elevated, but its present smooth form is the effect of repeated glacial erosion. Like Trout River village, this look-out is located on a deposit of marine gravel laid down at sea level by glacial meltwater about 12 000 years ago at the margin of the last retreating glacier. When the ice finally melted from Trout River ponds, the sea flooded in forming a marine terrace at the far end of the inner pond. Uplift has now excluded the sea so that a stream, Trout River itself, drains the large freshwater ponds. The lower terraces were cut as sea level returned to its present position (**Q**).

R Vue vers l'amont du lac Trout River Small Pond (depuis le belvédère)

Les falaises à droite, surraidies par les glaciers, sont soutenues par des gabbros (**13**), des dykes d'un complexe filorien (**14**) et des basaltes en coussins (**15**) résistants. Sur la gauche, les versants jaune-brun éloignés des Tablelands se composent de péridotite (**12**). Le versant le plus rapproché des Tablelands présente des gradins constitués de vieux blocs effondrés et affaissés, dont l'un est une grosse masse de gabbro, ainsi que, çà et là, des bancs de till de péridotite de couleur brune entraînés vers l'aval par le glacier. L'étendue boisée à l'avant-plan, des deux côtés du lac ainsi que les basses terres loin sur la droite, reposent sur le mélange facilement érodable (**18**).

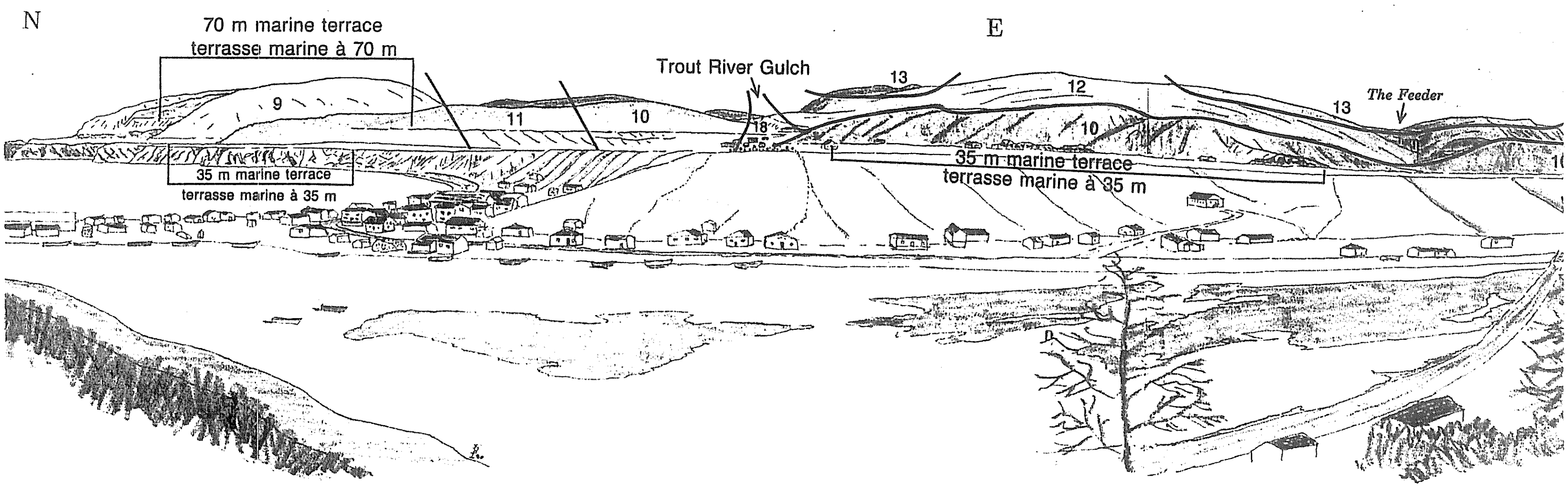
Le creusement de la vallée dû à l'érosion par les cours d'eau le long de failles raides s'est amorcé avant l'ère glaciaire et après le soulèvement du plateau que constituent les Tablelands, mais elle doit son aspect uniforme actuel à des épisodes d'érosion glaciaire souvent répétés. Tout comme le village de Trout River, le présent belvédère repose sur des graviers marins déposés au niveau de la mer par l'eau de fonte des glaciers il y a environ 12 000 ans en bordure du dernier glacier à se retirer. Éventuellement, après la fonte de la glace dans les lacs de la rivière Trout, la mer a envahi la région formant une terrasse marine tout à fait à l'extrémité du lac intérieur. Le soulèvement de la région a entraîné le retrait de la mer et maintenant un cours d'eau, soit cette même rivière Trout, draîne à lui seul ces grands lacs d'eau douce. Les terrasses basses ont été découpées au fur et à mesure que le niveau marin se réajustait, pour enfin atteindre son niveau actuel (**Q**).

Figure 10. *Panoramic view from the viewpoint above Trout River Pond. Original drawing and bilingual caption from Berger et al. (1992). The original drawing was by Ian Brookes.*

in what is now the Trout River Valley. Gravel pits along the road expose deltaic foreset beds, which in some cases show contorted sand and silt layers deformed by glacier push and slumping during rapid deposition.

The top of the delta is 35 m above present day sea level, and is depicted in Figure 11. More evidence of this former sea level stand can be found on both sides of the harbour, where an obvious rock platform extends from either side of the delta. The gravelly terrace, the rock platform and even more dramatically, a large raised sea stack called the "Old Man", together suggest that this regressional event was an important sea level stand. Radiocarbon dates obtained from shells (*Mya truncata*) indicate the delta was deposited 12 700 years ago.

Lower terraces in the village mark later stages in the decline of sea level to its present position. Traces of a higher terrace and beaches at 70 m asl are dated at 13 400 years ago.



Q Trout River panorama (from the path to the "Old Man" sea stack)

In the background is a cross-section of the Bay of Islands ophiolite suite and the other rocks that accompanied its travels from far out in Iapetus Ocean. The coastal hills are composed of deformed peridotite (**9**), gabbro (**10**), and granite (**11**). The Trout River Gulch on the skyline and the lowlands on the far right are underlain by mélange (**18**) which encloses large masses of gabbro and volcanics (**10**). Trout River Big Pond in the distance is carved from ophiolite rocks (**12-15; R**).

A broad terrace of gravel and sand at 35 m plugs the valley between Trout River Pond and the sea. It was deposited in the sea by meltwater flowing from a glacier which stood in the valley about 12 700 years ago. Sea level determined its flat top and also cut the "Old Man" sea stack and the prominent rock platform on the other side of the cove. Gravel pits by the roadside show contorted sand and silt deformed by glacier push and slumping during rapid deposition. On the far headland, traces of a higher 70 m terrace represent the marine limit, the highest level reached by the sea when glaciers withdrew from the outer coast about 13 400 years ago. Lower terraces in the village mark later stages in the decline of sea level to its present position.

Q Panorama de Trout River (du sentier jusqu'à l'éperon d'érosion marine «Old Man»)

À l'arrière plan se trouve une coupe transversale du complexe ophiolitique de Bay of Islands et d'autres roches qui l'ont accompagné lors de son déplacement depuis une grande distance au large dans l'océan Iapetus. Les collines côtières sont composées de péridotite (**9**), de gabbro (**10**) et de granite (**11**) déformés. Le ravin Trout River sur l'horizon et les basses terres loin à droite reposent sur le mélange ophiolitique (**18**) renfermant de grosses masses de gabbro et de roches volcaniques (**10**). Le lac Trout River Big Pond au loin a été découpé dans les roches ophiolitiques (**12-15; R**).

Une large terrasse de gravier et de sable d'une altitude de 35 m bouche la vallée entre le lac Trout River Pond et la mer. Cette terrasse a été déposée

Figure 11. *Sketch showing the 35 m asl terrace at Trout River. Original drawing and bilingual caption from Berger* et al. *(1992). The original drawing was by Ian Brookes.*

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