Current Research (1994) Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 94-1, pages 175-186

GEOLOGY OF CAMBRIAN–ORDIVICIAN PLATFORMAL ROCKS OF THE PASADENA MAP AREA (NTS 12H/4)

I. Knight
Newfoundland Mapping Section

ABSTRACT

The Pasadena map area contains a polydeformed sequence of limestone, dolostone, marble, phyllite, slate and metasandstone, and is part of the western Newfoundland foreland fold-and-thrust belt. The shelf sequence forms a sinuous belt that is bounded by allochthonous metasedimentary rocks of the Taconian Humber Arm Allochthon and its outlier, the Old Man Pond Allochthon. The terranes are unconformably overlain by Carboniferous fluvial and lacustrine sedimentary rocks of the Deer Lake Group in the southeast.

In the shelf sequence, the Late Cambrian to Middle Ordovician carbonate stratigraphy is basically similar to that elsewhere in western Newfoundland. Distinct facies variations are, however, apparent in the different thrust slices, as the succession is traced from west to east. In particular rocks, Middle to Upper Cambrian rocks record a prograding ramp- to shelf-sequence that includes deep-water ribbon limestones and shales, along with minor limestone conglomerate, crossbedded oolitic and oncolitic shoals and peritidal dolostones. The Early Ordovician Watts Bight Formation is dominated by lime grainstone rather than thrombolitic mounds. The Middle Ordovican Table Point Formation is characterized by a stylo-bedded and lumpy to brecciated limestone facies suggesting a deeper water origin than that elsewhere in western Newfoundland.

Several major thrust slices associated with large folds deform the shelf sequence. Small-scale structures indicate that early deformation consists of westward-verging thrusts typified by carbonate mylonites and bedding co-planar cleavage. In the west, the D1 structures are folded by D2 west-verging folding associated with a penetrative cleavage. D3 structures affecting both older set of structures consist of northeast-trending, east-verging folds and cleavage. To the north of the Old Man Pond Allochthon, east-trending folds and thrusts having a southward sense of vergence and predate the D3 structures. These south-verging structures fold the contact of the allochthon with the underlying shelf sequence. This results in the shelf sequence structurally overlying the allochthon locally on the overturned limbs of the folds. Facing directions in the shelf and allochthon sequence coincide, suggesting that the allochthon was, for the most part, an upright sequence overthrusting the shelf. A down-to-the-west extensional deformation affects the shelf and allochthon in the east of the area, close to the 'Helen's brook' fault.

Northwest-, west-, north- and northeast-trending faults cut the fold-and-thrust belt and have some Carboniferous reactivation locally. A few undeformed mafic dykes cut the flysch and carbonates.

Several marble prospects occur in the area. Pink- to red-dolomite marbles are common as are several off-white to white limestone marbles. Black marble including black arabescato (one locality) occurs in several localites.

Minor sphalerite and galena occur in veins and fractures cutting Cambrian dolostones and, rarely, dolostones of the Early Ordovician Watts Bight Formation. Grades are very low and no new base-metal showings were found.

INTRODUCTION

Cambro-Ordovician platformal rocks form a sinuous belt within the Pasadena map area. These mainly carbonate rocks have previously been mapped by Williams *et al.* (1982, 1983) and Gillespie (1983), but have lacked detailed internal subdivision applying recent stratigraphic nomenclature. Geological mapping of the area was begun in 1991 at 1:50 000 scale (Knight, 1992) following stratigraphic studies in 1990 (Knight and Boyce, 1991). Mapping was completed in 1993 although there are still significant problems to be resolved.

The area was mapped using two, 2-man field parties that reached the area via forest-access roads through Hughes Brook in the west and off Route 430 (Viking Highway) in

This project is funded by the Canada–Newfoundland Cooperation Agreement on Mineral Development (1990-1994); project carried by Geological Survey Branch, Department of Mines and Energy, Government of Newfoundland and Labrador.

the east. The Hughes Brook access road runs northward along Hughes Brook valley to Old Man Pond and then wanders northward through rugged mountains to Goose Arm and Wigwam Lake. A number of branch roads occur north and south of Old Man Pond and enter areas to the east of the road. A trunk road to Frenchman's Pond gives access to the area south of Goose Arm. In the east of the map area, gravel roads passing west through Nicholsville allow access to the carbonates of 'Pye's ridge', just north of Deer Lake (see Knight, 1992). However, the main access road begins near the town of Deer Lake incinerator, and runs west and then north to North Lake and the northern boundary of the area. The Goose Arm Pond road links the Hughes Brook and incinerator roads traversing the north-central part of the area along the Goose Arm Brook valley and Indian Dock Pond. Several minor woods-roads branch off this and the other roads. Other access to the area is provided by boat into Goose Arm and Penguin Arm and by canoe along some of the larger ponds. However, large areas are more remote and were reached by foot traverses.

The area is topographically rugged with many cliffs and steep slopes. Slopes are largely wooded. It is a fluvially and glacially dissected peneplain of approximately 300 to 400 m in the centre of the area and 200 to 300 m in the areas that fringe it to the west, north and east. Slopes are largely wooded. The highest areas occur in the vicinity of Old Man Mountain and west of Long Pond and to the west of Hughes Brook. In each instance the most elevated areas are underlain by resistent metasedimentary rocks of the Taconian allochthons that structurally overlie the carbonate terrane. The elevation of the carbonate-cored mountains gradually rises toward the heights attained by the allochthons.

GENERAL GEOLOGY

Shallow-water Cambrian–Ordovician siliciclastic–carbonate rocks form one of several geological terranes that comprise the western Newfoundland foreland fold-and-thrust belt. In the Pasadena map area, these rocks are part of a complex polydeformed terrane that outcrops in a sinuous belt sandwiched between the Taconian Humber Arm Allochthon (HAA) to the west and its easterly outlier, the Old Man Pond Allochthon (OMPA) (Figure 1). Early Cambrian to Early Ordovician passive margin sedimentary sequences were succeeded by a Middle Ordovician carbonate to flysch sequence, which was deposited in a foredeep above the collapsed margin during initiation of Taconian orogenesis. Both allochthons contain deep-water, metaclastic and carbonate rocks that are coeval with the shallow-water shelf succession (Cawood *et al.*, 1988; James *et al.*, 1989). The allochthons structurally overlie the shelf sequence, although the original contact is now significantly modified by the common deformations that affected both terranes.

The carbonate belt forms an asymmetrical horseshoe shape around the OMPA. Structures and stratigraphy trend north in the west but swing to the east around the northern perimeter of the allochthon. The carbonates then strike southwest for several kilometres along the southeast side of the allochthon to underlie 'Pye's ridge'. Southwest of this point, the carbonates are absent and the southeastern margin of the allochthon is marked by the structural contact with the Hughes Lake complex and overlying metasedimentary rocks of the Mount Musgrave group (Williams *et al.*, 1985; Williams and Cawood, 1989). The deformed shelf and allochthonous terranes are overlain unconformably by relatively undeformed basal conglomerates, red beds and lacustrine mudstones of the Mississippian Deer Lake Group. Small outliers of Carboniferous are locally present upon the lower Paleozoic carbonate rocks on some hillsides suggesting that some of the present topography may be an exhumed Carboniferous landscape (Bruckner, 1978; Knight, 1992).

Recent work indicates that the carbonate sequence has been structurally imbricated beneath the overriding allochthons. The details of stratigraphy and facies within the thrust slices change from west to east as noted previously by Knight and Boyce (1991), Knight (1992) and Boyce *et al.* (1992). The complex map pattern (Figure 2) reflects the superposition of at least three phases of structural shortening in the area. Early, west-vergent structures are overprinted by southeast-vergent structures throughout the western side of the belt. In the north however, south-verging structures are either coeval with, or postdate, the west-verging structures and are postdated by southeast-verging structures.

STRATIGRAPHY OF THE CAMBRO-ORDOVICIAN CARBONATE SHELF

Although the broad subdivisions of the carbonate shelf sequence can be mapped throughout the Pasadena map area, this study indicates that significant variations occur in the sequence from west to east. The details of these variations are already documented in Knight and Boyce (1991), Knight (1992) and Boyce *et al.* (1992) and are briefly summarized here.

CAMBRIAN ROCKS

In the west half of the map area (and preserved in the Penguin Head and Raglan Head thrusts), the succession begins with a basal sequence of mixed siliciclastic and carbonate rock of the Penguin Cove Formation (Lilly, 1963). This Middle Cambrian sequence consists of quartz arenite, dolomitic sandstone and siltstone, grey shale, mudstone and oolitic, oncolitic, intraclastic, skeletal and stromatolitic limestone. It is correlated with the Bridge Cove member, upper Hawke Bay Formation, Labrador Group of the Canada Bay area (Knight and Boyce, 1987, 1991).

The Penguin Cove Formation is conformably overlain by limestone and dolostone of the Middle to Late Cambrian Port au Port Group. At the base of the group is fossiliferous, oolitic, oncolitic and bioturbated dark-grey limestone of the Middle Cambrian March Point Formation. This is overlain by a thick succession of dolostone and limestone of the Petit Jardin Formation, which is markedly cyclic. A middle member of oolitic, stromatolitic and laminated limestone and

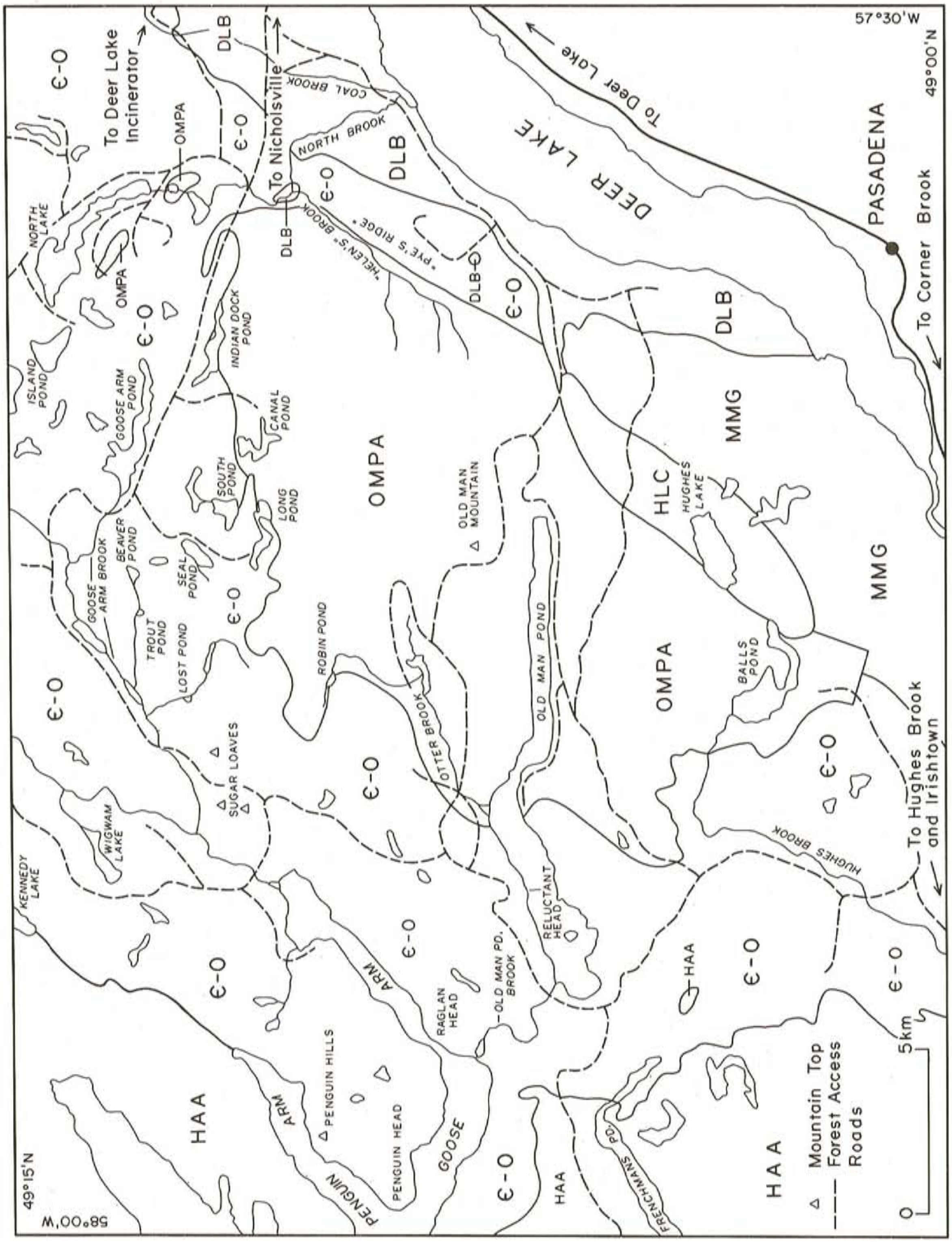
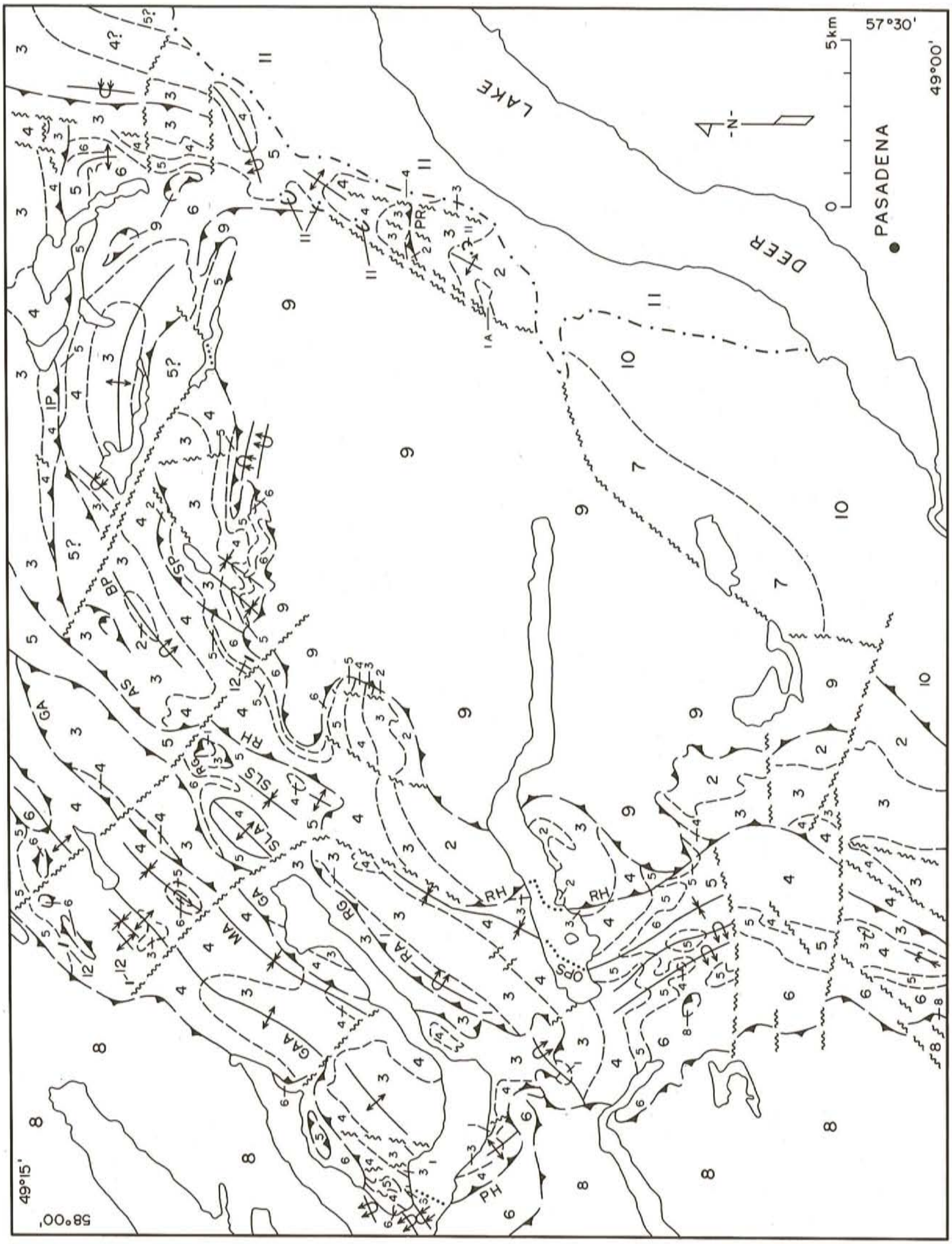


Figure 1. *Locality map and simplified geological map of the Pasadena map area (based on Williams and Cawood, 1989; Knight and Boyce, 1991; Knight, 1992, unpublished data).* **Є-O**–*Cambro-Ordovician parautochthon; HAA–Humber Arm Allochthon; OMPA–Old Man Pond Allochthon; HLC–Hughes Lake Complex; MMG–Mount Musgrave Group; DLB–Deer Lake Basin.*


DEER
LAKE
PASADENA
0
5 km
57°30'
49°00'
49°15'
58°00'

ROCKS OF UNKNOWN AGE

12 *Mafic dykes*

CARBONIFEROUS

11 *Deer Lake Group*

ALLOCHTHONOUS ROCKS

10 *Mount Musgrave Group (Precambrian to Cambrian?)*

9 *Old Man Pond Allochthon (Hadrynian to Ordovician?)*

8 *Humber Arm Allochthon (Hadrynian to Ordovician?)*

7 *Hughes Lake Complex (Hadrynian)*

PARAUTOCHTHONOUS ROCKS

ORDOVICIAN (Lower to Middle)

6 *Goose Tickle Group*

5 *Table Head Group*

4 *St. George Group*

CAMBRIAN (Middle to Upper)

3 *Port au Port Group*

2 *Reluctant Head Formation*

1 *Penguin Cove Formation*

1A *Psammite and pelite equivalent of Penguin Cove Formation?*

LEGEND

Stratigraphic contact

Unconformity

Fault

Thrust (teeth indicate hangingwall or hangingwall and dip; tine indicates dip if thrust is folded)

Fold axes (upright, recumbent)

Fold axes (now downward facing due to refolding)

PH *Penguin Head thrust*
GA *Goose Arm thrust*
RG *Raglan Head thrust*
RH *Reluctant Head thrust*
AS *Alder Steady thrust*
SP *Seal Pond thrust*
IP *Island Pond thrust*
PR *'Pye's ridge' thrust*

GAA *Goose Arm anticline*
RA *Raglan Head anticline*
BP *Beaver Pond anticline*
SLA *Sugar Loaves anticline*
SLS *Sugar Loaves syncline*
MA *Middle Arm syncline*
OPS *Old Man Pond syncline*

Figure 2. *Simplified geological map of the Pasadena map area that shows the distribution of major stratigraphic subdivisions and geological structures in the parautochthonous belt (based on Knight and Boyce, 1991; Knight, 1992, unpublished data).*

interbedded dololaminite separates lower and upper units of massive dolostone and dololaminite. The light-grey to grey dolostones are characteristically rusty-, buff- and yellow-weathering and microcrystalline to fine grained in texture.

At the top of the Port au Port Group is the Berry Head Formation. This latter unit has a thick basal succession of dominantly light-grey, fine-grained dolostones, containing chert, and an upper member of interbedded dark-grey limestone and light-grey dololaminite. The limestone includes bioturbated, thrombolitic, stromatolitic and parted types.

The Cambrian succession in the easterly thrust-slices differs from that in the western slices in three main ways. It includes at its base the Reluctant Head Formation, locally overlying a polydeformed psammite–pelite unit; it does not include the March Point Formation; and the Petit Jardin Formation is represented by only a single dolostone unit. The Berry Head Formation is essentially the same in both areas. However, in the most easterly thrusts, for instance those on 'Pye's ridge', there is a prominent conglomeratic unit at the base of the upper limestone–dolostone member, which is not seen elsewhere in the map area. A description of the Reluctant Head Formation is given in Knight and Boyce (1991) and Knight (1992).

LOWER ORDOVICIAN ROCKS

Lower Ordovican rocks collectively known as the St. George Group are divisible elsewhere in western Newfoundland into four formations; i.e., the Watts Bight, Boat Harbour, Catoche and Aguathuna formations (Knight and James, 1988). The group is not well exposed in the map area so that a full appreciation of it cannot be made. However, a few preliminary observations are possible. The lower part of the St. George Group is markedly cyclic but generally has thin dolostone caps. Dolomitization of limestones of the Watts Bight and Catoche formations is minor compared to the sections found on the Great Northern Peninsula and Port au Port Peninsula (see Knight and James, 1988).

The Watts Bight Formation is a succession of thick-bedded dark-grey to almost black limestones interbedded with thin dololaminites. The bituminous, cherty limestones occur in beds several metres thick and the dololaminites in beds less than 50 cm thick. Fine- to medium-grained, bituminous, dark-grey dolostone with a light-grey colour-mottling characterizes the basal few metres and localized patches within the formation. The formation is characterized by a lower part, dominated by thrombolitic mounds and bioturbated limestone and an upper part of dominantly peloidal-intraclastic grainstone–packstone having mounds. This formation is usually the best exposed part of the group.

The Boat Harbour Formation is generally poorly exposed and very commonly strongly deformed compared to adjoining units. The base of the formation is placed at the base of a thick dololaminite unit overlain by several metres of off-white to light-grey, laminated and thinly stratified limestone. Limestone–dololaminite metre-scale cycles occur in some areas but the dolostone interbeds are generally thin (i.e., < 50 cm). The limestones include bioturbated, stromatolitic, wavy thin-bedded and laminated limestones. Intraclastic grainstones are common in the limestones associated with the mounds. Trilobites, gastropods, cephalopods, crinoids and the trace fossil *Chondrites* occur locally in the less metamorphosed western thrust slices. The colour of the limestone and marbles varies from dark-grey, grey, light blue-grey through to off-white.

The Catoche Formation is a monotonous lower unit of dark-grey, dolomite-burrow-mottled limestone characterized by irregular dolomite seams and stylolites and an upper unit of ivory- to cream-coloured limestone. In the less marmorized parts of the map area, the lower limestone is locally fossiliferous with gastropods and cephalopods. Large thrombolite mounds occur just below the white limestone member at Old Man Pond and southward into Hughes Brook valley. In the marble belt in the east, the lower part of the lower limestone is dark-grey compared to the upper part, which is a light blue-grey. The upper white limestone is equivalent of the Costa Bay member of Knight and James (1988). It is a thinly stylo-stratified peloidal grainstone and burrow-mottled limestone. Dolostone is interbedded in the upper part of the member as it grades into the overlying Aguathuna Formation. However, locally no evidence of the white limestone has been found suggesting it was eroded locally beneath the St. George Unconformity (Knight *et al.* 1991).

The Aguathuna Formation is a succession of yellow-weathering, light-grey microcrystalline dolostone with subordinate laminated, microbial and bioturbated, fine-grained, light-grey to off-white limestone interbeds. Although thickly developed (~ 20 m thick) in some areas, for example, Old Man Pond, Goose Arm road at the head of Goose Arm and Penguin Head, it is either very thin or absent in other areas, for instance at 'Pye's ridge' and Long Pond. This suggests significant erosion beneath the St. George Unconformity.

MIDDLE ORDOVICIAN CARBONATES

Middle Ordovican limestones of the Table Point Formation (Table Head Group) form the uppermost carbonate beneath the overlying flyschoid rocks of the Goose Tickle Group. The formation is divided into a lower member of interbedded limestone and dolostone, the Spring Inlet Member (Ross and James, 1987) and an upper unnamed member of monotonous dark-grey limestone. In the western areas of the map area, the Spring Inlet Member comprises bioturbated to stylo-nodular limestone, fossiliferous, oncolitic and crossbedded grainstone, parted dolomitic limestone, laminated and fenestral-laminated limestone, and dololaminite. The overlying upper member is dominantly thick-bedded, stylobedded limestone, throughout the area. However, in the east, the limestone is associated with rubbly limestones of centimetre-sized fragments with common crinoidal detritus visible. The rubble, which is set in a dolomitic limestone matrix, is very common at the top of the formation throughout the eastern part of the map area, e.g., North Lake and Long Pond. It is capped by a decametre-thick, limestone conglomerate consisting of angular pebble- to boulder-size (locally blocks) clasts of massive, stylobedded, fine-grained and shaly limestone set in a shaly limestone matrix. This rock type is generally assigned to the Daniel's Harbour member of the Goose Tickle Group.

MIDDLE ORDOVICIAN FLYSCH

The Goose Tickle Group in the eastern thrust-slices comprises dolomitic ribbon limestone, dolostone and platy limestone conglomerate interbedded in dark-grey to silvery-grey slate and phyllite with very minor thin sandstone. It occurs just beneath the OMPA. The abundance of fine-grained and conglomeratic carbonate in the phyllite means they bear a striking resemblance to rocks of the Reluctant Head Formation–Weasel group (Knight and Boyce, 1991; Boyce *et al.*, 1992). This has resulted in the unit being assigned to the Cambrian Reluctant Head Formation at North Lake, at Long Pond and west of Long Pond (Williams *et al.*, 1983; Williams and Cawood, 1989; Waldron and Milne, 1991). Although these rocks are locally polydeformed, as near North Lake and Long Pond, there is no marked structural discordance across the Table Head–phyllitic-ribbon limestone contact. Bedding attitudes and facing directions on the ribbon limestone beds indicate that they conformably overlie the rubbly limestone of the top of the Table Point Formation. This suggests that they are a facies comparable to the Table Cove Formation of the Table Head Group (see Stenzel *et al.*, 1990). No fossil evidence is, however, available to confirm or deny this interpretation. If the phyllitic-ribbon limestones do belong to the Reluctant Head Formation, they would have to be an upright sequence that was structurally emplaced above the Table Head Group and beneath the Old Man Pond Allochthon.

Along the western edge of the belt, the Goose Tickle Group occurs beneath the HAA and consists of dark-grey slate, green-grey sandstone, thin-laminated and crosslaminated siltstone, laminated fine-grained dolostone and limestone, and thick beds of massive and conglomeratic dark-grey limestone. In Penguin Arm and Goose Arm, the sequence is polydeformed and locally resembles broken formation and melange. Green-grey and blue-grey mudstones resembling rocks of the Middle Arm Point–Northwest Arm Formation of the Taconian allochthons in western Newfoundland (Williams and Cawood, 1989; Knight, 1986) occur very locally within the broken flysch formation on the south shore of Goose Arm.

MAFIC DYKES OF UNKNOWN AGE

Dark green-grey, fine-grained mafic dykes intrude the carbonates and flysch in the map area. A single dyke is located along the bank of Lost Pond brook, 3 km west of Long Pond. It trends subvertically at 025° and cuts slate and thin-bedded dolostone. A dyke intrudes Table Head Group carbonates 3 km west of Wigwam Lake, just east of the structural contact with the HAA. Contacts with the limestone are not exposed but the dyke appears to trend almost due north.

CARBONIFEROUS ROCKS

Carboniferous rocks unconformably overlie the deformed carbonate terrain and the allochthonous and other metasedimentary terranes in the southeast corner of the map area. The rocks that form the northwestern edge of the Deer Lake Basin (Hyde, 1979, 1983) belong to the North Brook and Rocky Brook formations of the Deer Lake Group. Narrow Carboniferous paleo-cave deposits occur along fractures in the carbonate belt at a number of localities throughout the map area (Knight, 1992).

A basal limestone conglomerate is draped around the slopes of 'Pye's ridge' and other ridges in the neighbourhood. Its presence in the bottom of valleys as at 'Helens brook' and North Brook and high on the north slopes of 'Pye's ridge' indicates that the hilly topography of the carbonate terrane adjacent to the Deer Lake Basin is an exhumed Carboniferous one (Bruckner, 1978). Calcareous roots (rhizoliths) occur in the conglomerate locally (Knight, 1992).

To the southwest of 'Pye's ridge', the North Brook Formation comprises friable red sandstone, pebbly sandstone and conglomerate. Along the southeastern slope of the 'ridge', the formation is dominated by red sandstone and siltstone. Traced to the northeast, where the incised valley of Coal Brook enters the carbonate terrane, the Carboniferous rocks comprise drab, olive-green mudstone and thin limestone of the Rocky Brook Formation. Here, stromatolite encrusts both the unconformity and carbonate pebbles and cobbles just above the surface. The unconformity is steeply inclined to the southeast with numerous ledges and small cliffs suggesting a hillside. The limestone are pungently bituminous.

STRUCTURE

The lower Paleozoic shallow-water carbonate rocks of the Pasadena map area are part of a polydeformed duplex beneath a roof thrust located at the base of the OMP and HA allochthons. The sole thrust is not exposed. Studies of selected areas of NTS 12H/4 indicate that there are three main phases of compressive deformation. One extensional deformation occurred locally in the area (Knight and Boyce, 1991; Waldron and Milne, 1991; Knight, 1992).

Within the western part of the carbonate belt, westward-verging thrusting was associated with and followed by west-verging folding. It was superceded by east-verging recumbent folding that deformed the earlier thrusts and folds including the roof thrust (Knight and Boyce, 1991; Knight, 1992).

Mapping during 1993 also indicates that there is significant south-verging, east-trending recumbent folding and thrusting that affects the carbonates and earlier thrusts and the OMPA–carbonate contact around the northern edge of the OMPA. It appears to predate the east-verging D3 folding and is itself truncated in the east by north-trending, east-verging structures.

A late down-to-the-northwest extensional cleavage occurs locally in the east (Waldron and Milne, 1991; Knight, 1992). All these deformations predate the intrusion of the mafic dykes and the deposition of the Mississippian Deer Lake Group.

It is important to emphasize however, that there are a number of areas of the thrust belt where stratigraphic and structural relationships are still unclear. This includes the trace and branch points of several thrusts and the assignment of folds to definite phases of the deformation. The paucity of fossil remains in the carbonates of the structurally complex high-strain areas creates uncertainty about the age of rock units. Structural cross sections through the area have yet to be attempted to test the validity of the mapping. Stratigraphic relationships, cleavage-bedding, cleavage-cleavage, facing directions of beds (tops) and, where available, fossil data, have been used to interpret the structural relationships and map patterns shown in Figure 2. Tops are defined using crossbeds, crosslamination, tepee structures, scours, stromatolite mounds and fabrics, mudcracks and stratigraphic order within small-scale cycles. The structural interpretation outlined here draws heavily upon a few critical areas where exposure has allowed detailed resolution of structural relationships.

THRUSTS

From west to east, the main west-verging thrusts are the Penguin Head, Goose Arm, Raglan Head, Reluctant Head, Alder Steady and Seal Pond thrusts. The Alder Steady thrust may be the northeastward continuation of the Reluctant Head thrust. Many of these thrusts can be traced to branch points with the sole thrust(s) of the allochthons. The Island Pond thrust, which occurs in the north of the area, is a south-verging structure. The 'Pye's ridge' thrust and a north-trending east-verging thrust north of the incinerator road occur in the east.

Relationships associated with the Penguin Head and Reluctant Head thrusts suggest that these thrusts have been folded or steepened principally by the later east-verging deformation (see Knight and Boyce, 1991; Knight, 1992). The structural relationships near Old Man Pond Brook, the head of Goose Arm and along the valley of Goose Arm Brook suggest complex culminations and structural depressions (e.g., Sugar Loaves anticline and syncline). These are associated with high-strain zones close to the leading edge of the Goose Arm, Raglan Head and Reluctant Head thrusts. Part of the edge of the Reluctant Head thrust is a subvertical shear zone noted previously by Knight and Boyce (1991). Several topographic lows cut down through the Penguin Head thrust into footwall rocks of the Goose Tickle Group to the northwest and northeast of Wigwam Lake. The structural culmination cored by rocks of the Table Head and possibly Goose Tickle groups, east of the head of Goose Arm may also be part of the Penguin Head thrust footwall.

West-verging anticlines and synclines, associated with an east-dipping penetrative cleavage, are mapped in the hangingwall and footwalls respectively, of most of the thrusts. The major structures are the Goose Arm, Raglan Head and Beaver Pond anticlines and the Middle Arm and Old Man Pond synclines. The Penguin Head thrust is marked by a sharp contact with a narrow shear zone in the hangingwall, whereas the Raglan Head and Goose Arm thrusts have broad foliated and mylonitic zones in hangingwalls and/or footwalls. Complex polydeformation characterizes the footwalls and hangingwalls of the Reluctant Head, Alder Steady, Seal Pond and 'Pye's ridge' thrusts. Transposition of bedding, sheath folds and refolded folds and cleavages commonly occur, especially above the soles of the thrusts, in phyllitic thin-bedded limestones of the Reluctant Head Formation (Knight and Boyce, 1991; Knight, 1992). Formations and members are cutout against several of the thrusts, e.g., against the hangingwall of the Penguin Head thrust north and south of Goose Arm, and the footwall to the roof thrust beneath the allochthons.

THE CONTACT OF THE ALLOCHTHONS AND THE CARBONATE BELT

The HAA structurally overlies the carbonate and flyschoid rocks of the carbonate belt. Where shaly flyschoid rocks underlie the contact, they are intensively flattened, e.g., south of Frenchman's Pond. Tectonically interleaved rocks of the Table Head Group are also commonly flattened in the same area.

Stratigraphic cutoff of Cambrian to Ordovician carbonate units and of the intensely flattened flysch beneath the OMPA, north and south of Old Man Pond, suggests that the relationships in this area are post-flattening (i.e., post early emplacement), but predate later folding of the contact of the OMPA and the carbonates. Locally, as near Old Man Pond, South Pond and Indian Dock Pond, the carbonates structurally overlie the allochthon. However, mapping shows that these are the overturned limbs of southward-verging, east-trending recumbent folds. Facing directions in both the allochthon and the carbonates as they are traced around the folds indicate that the two terranes were part of an upright structural stack before the later folding occurred. The contact and bounding carbonate–allochthon rocks are folded about northeast-trending D3 folds near Long Pond and northwest of Balls Pond.

Along the southeast edge of the OMPA, the kinematic indicators on structures associated with the 'Helens brook' fault suggest that the allochthon was juxtaposed against marbles of 'Pye's ridge' by down-to-the-northwest extension (Knight, 1992). However, in view of the multiple folding of the allochthon and underlying Goose Arm duplex, the timing of this deformation may be earlier rather than later, and is now reoriented.

Small outliers of allochthon mapped in the North Lake area structurally overlie polydeformed flyschoid rocks. Similiar outliers of the HAA rest upon flysch just to the southwest of Old Man Pond.

POLYDEFORMATION SHOWN BY SMALL-SCALE STRUCTURES

The earliest structure noted throughout the area is a bedding-parallel foliation that is penetrative in limestone beds that are interbedded with dolostone. Boudinage of dolostone beds and small-scale thrusts are common in these units and can be seen in the cliffs west of, and overlooking, the south end of the Hughes Brook valley (Figure 3). A strong mylonite is locally developed in the hangingwall. Augen tails to the boudins and smaller shear fabrics indicate that the sense of overthrusting is to the west.

Second-phase structures are west-verging folds with an associated cleavage that deform the D1 thrusts, mylonites and foliation. The folds vary in size and locally attain mountain scale as at Raglan Head.

The third deformation is characterized by northeast-trending, east-verging structures. Associated cleavage appears to be locally developed, generally crenulating the earlier S1 and S2 structures. However, D3 folds are well developed in some areas and are believed to control the outcrop pattern in the area of Goose Arm where they fold the Penguin Head thrust and its bounding walls. A downward-facing synformal anticline and antiformal syncline pair mapped in a cliff looking south over Irishtown are believed to be D2 or possibly D1 structures reoriented by D3 folding. A steeply west-dipping cleavage associated with the folds is also a D2–D1 structure that is reoriented by the D3 deformation.

The northeast-trending fold axes locally interfere with east-trending south-verging folds in the Long Pond and South Pond area. This suggests that the timing of the south-verging folds predates the D3 folds. The folds, which include large, east-trending periclinal structures are associated with high-angle thrusts that overthrust to the south, for example the Island Pond thrust and a postulated thrust along Goose Arm Pond. Re-evaluation of 'Pye's ridge' thrust and associated structures suggests that it is a south-verging structure folded about a northeast-trending, east-verging D3 fold.

ECONOMIC GEOLOGY

BASE METALS

Minor base-metal mineralization is known in the map area and has been the target of past exploration (Westfield Minerals Limited, 1983 a, b, and references contained therein). Galena, sphalerite, pyrite and minor chalcopyrite occur in the massive dolostones of the Petit Jardin, Berry Head and Watts Bight formations. The mineralization is mostly associated with fracture systems that cut the dolostones, with some disseminated mineralization in adjacent vugs, intergranular porosity and along stylolites. The zones can locally be traced over a few metres along the fractures but grades are low, rarely exceeding 2 percent Zn and 7000 ppm Pb. No new showings were added to those already known from previous exploration.

DIMENSION STONE

The Pasadena map area is potentially rich in marble dimension-stone deposits. Marble deposits are currently being evaluated at 'Pye's ridge' following their discovery in the late 1980's. Off-white marbles including arabescato were identified in rocks of the upper Berry Head Formation and in the white limestone member of the Catoche Formation (Costa Bay member) (Knight, 1992). Light to dark blue-grey, stylolitic mottled marbles occur in the Catoche Formation. The lighter marbles are locally pink to red in colour close to the unconformity with the Carboniferous and near faults and fractures.

White marbles of the Costa Bay member are present elsewhere in NTS map area 12H/4. A fine-grained white marble is present in float beneath the cliffs on the north side of Hughes Brook where a gorge extends east to Balls Pond. This is probably the same marble that outcrops in a steep, north-facing valley 2.5 km south of Old Man Pond and just east of the main forest-access road to Goose Arm. Here, the unit is at least 20 m thick consisting of thick beds of massive and stylolitic marble. Elsewhere in the area this marble, which is not well exposed, is commonly sugary in texture. To the northeast of 'Pye's ridge', the fine-grained, off-white marble is interbedded with grey dolostone beds.

The lower white marbles of the Berry Head Formation are not well exposed away from 'Pye's ridge' and appear to be mostly dolomitized. Dolomitic marbles are common in the area between Balls Pond and Hughes Brook valley to the west. Purple spotting and mottling is common in these creamy to light-grey dolostones. The dolostones are often heavily fractured and massive types may be difficult to locate.

Dark-grey marbles are best located in the area southwest and northeast of North Lake. These belong to the Watts Bight and Table Point formations. The marbles of the Watts Bight Formation are thick bedded, dark-grey to almost black, fine to coarsely crystalline and some have a grey mottling. They are hard and massive at the east end of the Goose Arm Pond pericline and the outcrop belt northeast of North Lake.

The marbles of the Table Point Formation in the North Lake area are not so dark and massive as those of the Watts Bight Formation but include thick beds of stylolitic, burrow-mottled and calcite veined limestone. The marbles are fine to medium crystalline. Thick beds of conglomeratic marble from the top of the formation may be useable as a dark-grey arabescato.

POROUS DOLOMITE

A late-stage dolomite is common replacing Ordovician limestone at or below the main thrusts and in some of the main folds. The dolomite is sugary textured, dull grey in colour and commonly porous. It is rarely mineralized and clearly suggests structurally controlled dolomite hydrocarbon reservoir rocks occur in the foreland fold-and-thrust belt.

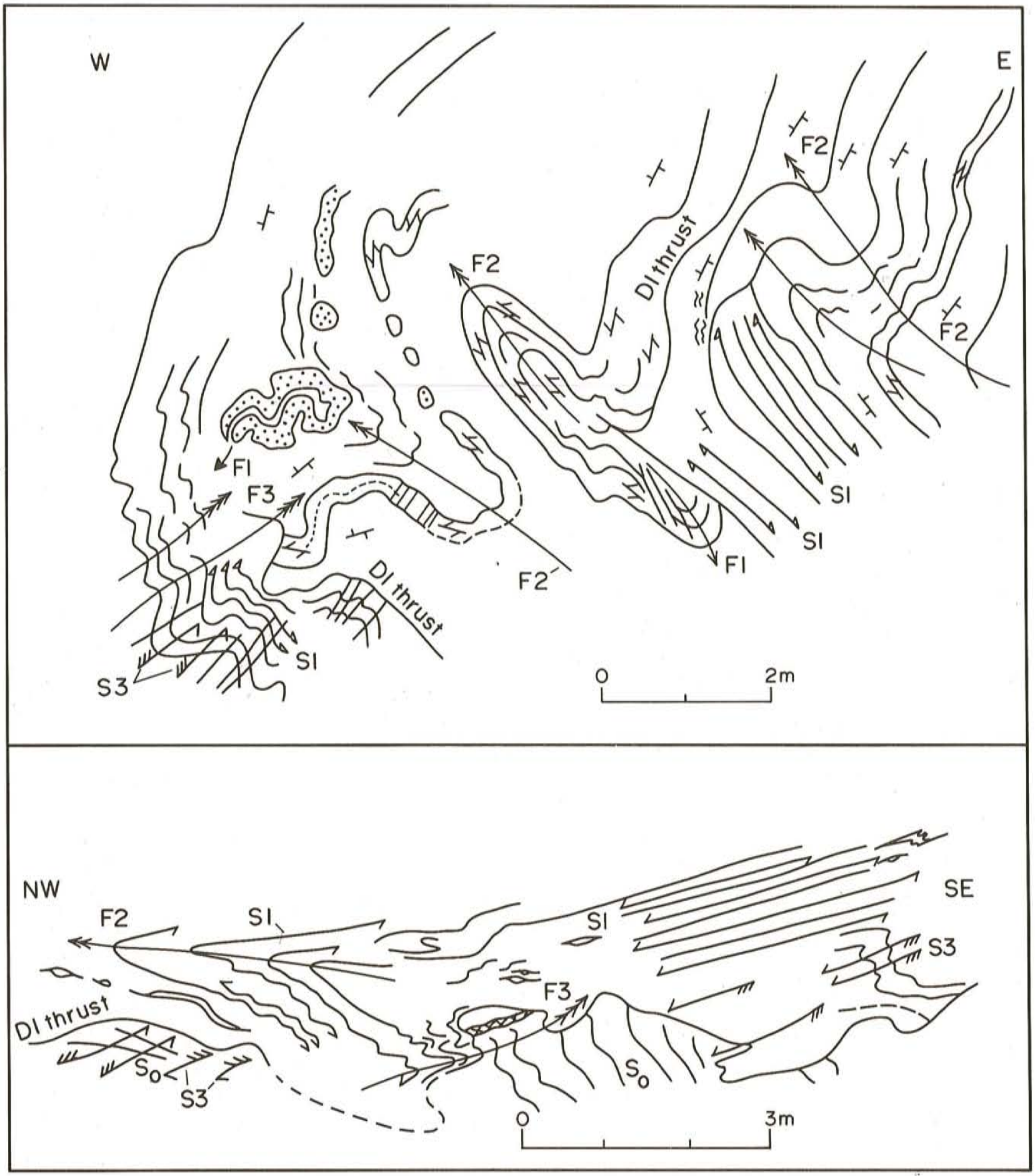


Figure 3. *Measured geological field sketches of polydeformed carbonate rocks of the uppermost Port au Port Group in hills overlooking Hughes Brook. DI thrusts are deformed by D2 west-verging folds and cleavage and both folded and crenulated by east-verging D3 folds and cleavage. Stippled bed in upper half of the figure represent chert nodules. —limestone, —dolostone. So—bedding; SI, S2, S3 = DI to D3 cleavage; FI, F2, F3 = DI to D3 fold axes; —dolomite or calcite augen with kinematic tails.*

ACKNOWLEDGMENTS

This study would not have progressed as far without the able mapping assistance of Dean Fraser in 1991 and 1993, and Don Dunphy, Lori Dwyer and Lisa Benson in 1993. Doug Boyce and Steve Ash provided paleontological assistence. Brian O'Brien is thanked for his encouragement to tackle the structural puzzles of the NTS 12H/4 map area. Steve Colman-Sadd read the article.

REFERENCES

Boyce, W.D., Knight, I. and Ash, J.S.
1992: The Weasel group, Goose Arm area, western Newfoundland: lithostratigraphy, biostratigraphy, correlation and implications. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 92-1, pages 69-83.

Bruckner, W.D.
1978: Exhumed pre-Carboniferous landforms in west Newfoundland. Abstract, Eastern Canada Palaeontology and Biostratigraphy Seminar, Corner Brook, Newfoundland.

Cawood, P.A., Williams, H., O'Brien, S.J. and O'Neill, P.P.
1988: A geological cross section of the Appalachian orogen. Geological Association of Canada, Mineralogical Association of Canada and Canadian Society of Petroleum Geologists, Joint Annual General Meeting, Field excursion guidebook A1, 160 pages.

Gillespie, R.T.
1983: Stratigraphic and structural relationships among rock groups at Old Mans Pond, west Newfoundland. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, 198 pages.

Hyde, R.S.
1979: Geology of Carboniferous strata in portions of the Deer Lake Basin, western Newfoundland (12A, 12 H). Newfoundland Department of Mines and Energy, Mineral Development Division, Report 79-6, 43 pages.

1983: Geology of the Carboniferous Deer Lake Basin. Newfoundland Department of Mines and Energy, Map 82-7.

James, N.P., Barnes, C.R., Stevens, R.K. and Knight, I.
1989: A Lower Paleozoic continental margin carbonate platform, northern Canadian Appalachians. *In* Controls on Carbonate Platforms and Basin Development. *Edited by* T. Crevello, R. Sarg, J.R. Read and J.L. Wilson. Society of Economic Paleontologist and Mineralogists, Special Publication 44, pages 123-146.

Knight, I.
1986: Ordovician strata of the Pistolet Bay and Hare Bay area, Great Northern Peninsula, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 147-160.

1992: Geology of marmorized, Lower Paleozoic, platformal rocks, 'Pye's ridge', Deer Lake. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 92-1, pages 141-157.

Knight, I. and Boyce, W.D.
1987: Lower to Middle Cambrian terrigenous-carbonate rocks of Chimney Arm, Canada Bay: lithostratigraphy, preliminary biostratigraphy and regional significance. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, page 359-365.

1991: Deformed lower Paleozoic platform carbonates, Goose Arm-Old Man's Pond. *In* Current Reasearch. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 141-154.

Knight, I. and James, N.P.
1988: Stratigraphy of the Lower Ordovician St. George Group, western Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 88-4, 48 pages.

Knight, I, James, N.P. and Lane, T.E.
1991: The Ordovician St. George Unconformity, northern Appalachians: the relationship of plate convergence at the St. Lawrence Promontory to the Sauk-Tippecanoe sequence boundary. Geological Society of America Bulletin, Volume 103, pages 1200-1225.

Lilly, H.D.
1963: Geology of Hughes Brook-Goose Arm area. Memorial University of Newfoundland, Geology Report 2, 123 pages.

Ross, R.J. Jr. and James, N.P.
1987: Brachiopod biostratigraphy of the Middle Ordovician Cow Head and Table Head groups, western Newfoundland: Canadian Journal of Earth Sciences, Volume 24, pages 70-95.

Stenzel S.R., Knight, I. and James, N.P.
1990: Carbonate platform to foreland basin: revised stratigraphy of the Table Head Group (Middle Ordovician), western Newfoundland. Canadian Journal of Earth Sciences, Volume 27, pages 14-26.

Waldron, J.W.F. and Milne, J.V.
1991: Tectonic history of the central Humber Zone, western Newfoundland Appalachian, post-Taconian deformation of the Old Man's Pond area. Canadian Journal of Earth Sciences, Volume 28, pages 398-410.

Westfield Minerals Limited
1983a: Report on 1982 exploration Brinco Goose Arm concession area NTS 12H/4,5. Unpublished report. Newfoundland Department of Mines and Energy, Geological Survey Branch. [Nfld 12H (807)]

1983b: Brinco Goose Arm concession area NTS 12H/4, 12H/7. Report on 1983 exploration. Unpublished report. Newfoundland Department of Mines and Energy, Geological Survey Branch. [Nfld 12H (839)]

Williams, H., Gillespie, R.T. and Knapp, D.A.
1982: Geology of the Pasadena map area, Newfoundland. *In* Current Research. Geological Survey of Canada, Paper 82-1A, pages 281-288.

1983: Geology of Pasadena map area, 12H/4, Newfoundland. Geological Survey of Canada, open file 928, map with side notes.

Williams, H., Gillespie, R.T. and van Breemen, O.
1985: A late Precambrian rift-related igneous suite in western Newfoundland. Canadian Journal of Earth Sciences, Volume 22, pages 1727-1735.

Williams, H. and Cawood, P.A.
1989: Geology, Humber Arm Allochthon, Newfoundland. Geological Survey of Canada, Map 1678A (1:250 000).

Note: Geological Survey Branch file numbers are included in square brackets.