

INTERNAL AND EXTERNAL RELATIONSHIPS OF THE ORDOVICIAN ROBERTS ARM GROUP IN PART OF THE SPRINGDALE (NTS 12H/8) MAP AREA, WEST-CENTRAL NEWFOUNDLAND

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ABSTRACT

In the Loon Pond–Rocky Pond area southeast of Halls Bay, the Ordovician Roberts Arm Group is tectonically attenuated. There, it occurs in the regional hanging-wall sequence of a southeast-directed, folded, imbricate fault system that forms part of the Red Indian Line structural zone.

Volcanic rocks assigned to Unit 4 and Unit 6 form the bulk of two, regionally extensive, non-contiguous, fault-bounded lithostratigraphic panels. They may represent different tectonic levels of the original Roberts Arm Group. However, only the northeastern tract (Unit 4) is known to be in direct contact with the Crescent tholeiite belt and, therefore, only it is thought to underlie the younger sedimentary rocks of the Crescent Lake Formation.

The tectonomagmatic evolution of the Early Ordovician Hall Hill complex, west of the Mansfield Cove Fault, mostly predates that of the Roberts Arm Group. By comparison, the Early and Middle Ordovician Sops Head Complex records coeval and younger intervals of deposition than those documented in the Roberts Arm Group. Immediately east of the Tommys Arm Fault, the unbroken formations of the Sops Head Complex show a more complex metamorphic and plutonic history than seen in most of the Roberts Arm Group. This suggests that the Hall Hill complex and the Roberts Arm Group adjacent to the Silurian Springdale Group had a different orogenic development from the Roberts Arm Group adjacent to the Sops Head Complex.

INTRODUCTION

In the Loon Pond–Rocky Pond area southeast of Halls Bay, the Ordovician Roberts Arm Group forms a variably deformed, metamorphosed and altered lithotectonic assemblage that outcrops between the northwesterly adjacent Hall Hill complex and the southeasterly adjacent Sops Head Complex (Figure 1). Bounded by steeply northwest-dipping faults, the dominantly volcanic and subvolcanic rocks of the Roberts Arm Group are structurally overlain by the older plutonic rocks of the Hall Hill complex and structurally underlain by age-equivalent and younger sedimentary strata of the Sops Head Complex.

The area surveyed is tectonically situated on the northwest limb of the Z-shaped Notre Dame Bay orocline (Williams, 1962, 1963). Rocks strike northeastward within a variably doubly plunging periclinial fold, which is regionally demarcated by several high-angle reverse faults (Figure 2). The folded reverse fault separating the Roberts Arm Group and the Sops Head Complex is thought to locally define the Red Indian Line (Williams *et al.*, 1988). The

northeast-trending volcanosedimentary strata of the Roberts Arm Group become tectonically attenuated toward the southwest concomitantly with a southwestward transition from phyllite to hornfelsic schist within the underlying Sops Head Complex.

USAGE OF CHRONOSTRATIGRAPHIC AND BIOSTRATIGRAPHIC TERMS

In this paper, Ordovician series and stage boundaries come from Okulitch (2001), as do most estimates of their absolute age. The oldest Silurian rocks, located at the base of the Rhuddanian stage of the Llandovery series, are 443 ± 2/-4 Ma in age within Dunnage Zone correlatives in the Southern Uplands of Scotland (Tucker and McKerrow, 1995). The youngest Cambrian rocks, found immediately below the basal Tremadocian *Iapetognathus fluctivagus* conodont zone at Green Point, western Newfoundland (Cooper and Nowlan, 1999), are not absolutely dated at the base of the global Tremadocian stratotype section in the Newfoundland Humber Zone. However, they are precisely dated at 489 ± 0.6 Ma within the uppermost Cambrian of

Avalonian North Wales (Landing *et al.*, 2000). So defined, the Ordovician Period is 44 My in duration, extending from ca. 488 to 444 Ma.

To use British terminology, the base of the Late Ordovician is taken at the base of the Aurelucian stage of the Caradoc series (Fortey *et al.*, 1995). This is coincident with the base of the *Nemagraptus gracilis* graptolite biozone. The top of the revised Llandeilian stage of the Llanvirn series is drawn at the base of the *N. gracilis* Zone. So defined, the Llandeilian occupies the *Hustedograptus teretiusculus* graptolite biozone and is Middle Ordovician in age.

The base of the *H. teretiusculus* Zone is estimated to be 460.4 ± 2.2 Ma (Tucker and McKerrow, 1995) as the *Glyptograptus teretiusculus* graptolite biozone (*ibid*) is equivalent to the *H. teretiusculus* Zone. An estimate of the absolute age of the traditional 'late Llandeilo–early Caradoc' boundary in England comes from the Sm–Nd age of garnet-bearing volcanic rocks dated as 457 ± 4 Ma (Thirlwall and Fitton, 1983; *see also* the $458 \pm 2/4$ Ma age referenced by Okulitch, 2001). The absolute age of part of the upper portion of the *N. gracilis* Zone (the Costonian substage of the late Aurelucian) is believed to be 456.1 ± 1.8 Ma (Tucker and McKerrow, 1995). This is in agreement with the recent ^{40}Ar – ^{39}Ar age determination of ca. 455 Ma for the base of the overlying *D. multidentis* (or *C. bicornis*) graptolite biozone (Min *et al.*, 2001). Accordingly, the maximum absolute age range of the *N. gracilis* Zone probably extends from ca. 461 to 456 Ma. The lowermost Upper Ordovician (the base of the *N. gracilis* Zone) has been assumed to be ca. 460 Ma (Okulitch, 2001), although an estimate as old as 461.4 Ma has been postulated (Cooper, 1999).

Using proposed international terminology, the Upper Ordovician–Middle Ordovician boundary is the Caradocian–Darriwilian boundary (Mitchell *et al.*, 1997). The revised British Llandeilian stage now resides in the upper part of the global Darriwilian stage. In the Newfoundland Dunnage Zone, the Caradocian–Darriwilian boundary is mostly commonly located below the widespread Caradocian black shales within volcanosedimentary sequences that contain either chert or limestone. In western Notre Dame Bay, this biostratigraphic horizon is probably not significantly older than ca. 460 Ma (McConnell *et al.*, 2002). The base of the Darriwilian is coincident with the base of the *Undulograptus austrodentatus* graptolite zone, which is present in central Newfoundland (Williams and Tallman, 1995; O'Brien *et al.*, 1997) and defined precisely at 464 ± 2 Ma in Argentina (Huff *et al.*, 1997).

The absolute age range of the *Undulograptus austrodentatus* graptolite zone is critical for any time comparison of the Arenig–Llanvirn boundary with the Rangerian–

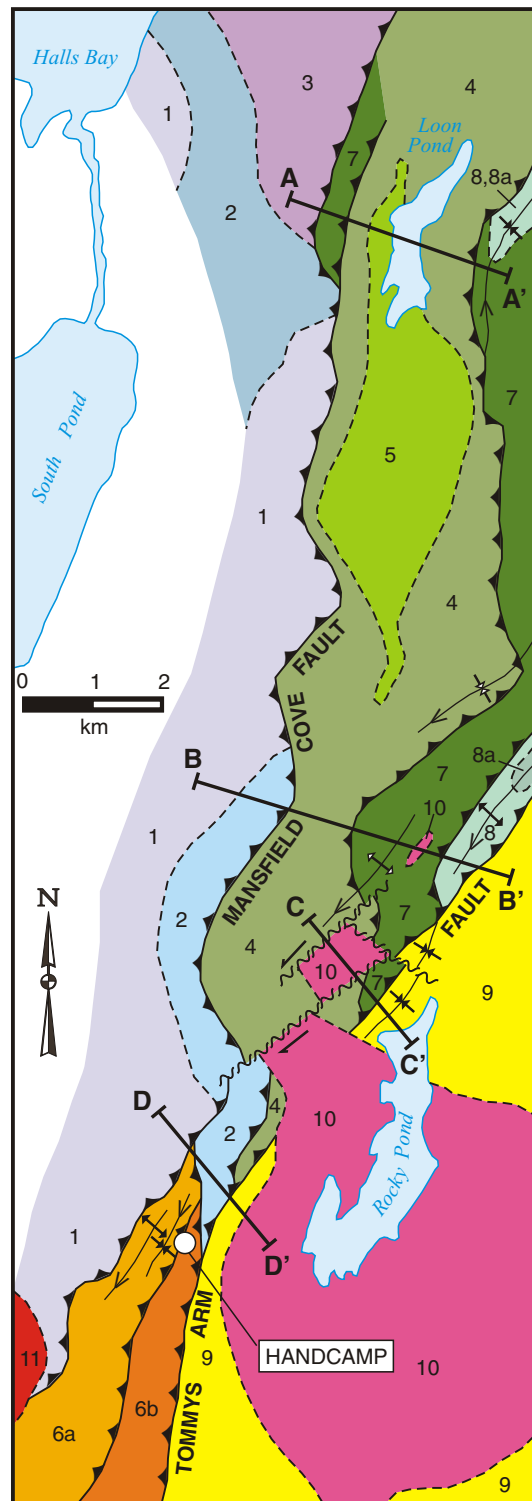


Figure 1. Simplified geological map of the Roberts Arm Group and adjacent units in the Loon Pond–Rocky Pond map area (NTS 12H/8).


Kanoshian boundary (lower Whiterockian of North America). It is also important for positioning the lower boundaries of the Llanvirnian and Whiterockian series relative to the

LEGEND (Figure 1)

EARLY SILURIAN - DEVONIAN

TOPSAILS INTRUSIVE SUITE

GULL BROOK SYENITE


-  **UNIT 11** - *Late Silurian - Devonian (?)*: mainly potassium feldspar-bearing syenite; subordinate quartz-rich hornblende-bearing granite

EARLY - LATE SILURIAN

HODGES HILL INTRUSIVE SUITE

TWIN LAKES DIORITE COMPLEX (?)


ROCKY POND GRANODIORITE

-  **UNIT 10** - *Late Ordovician - Early Silurian (?)*: mainly biotite - hornblende granodiorite (locally chloritic and quartz veined); subordinate hornblende porphyritic quartz diorite and associated dykes; minor satellite body of foliated quartz tonalite; marginal sheets of gabbro, granodiorite, granite and aplite

LATE EARLY ORDOVICIAN - LATE MIDDLE ORDOVICIAN

SOPS HEAD COMPLEX


Unbroken formation

-  **UNIT 9** - *Early Middle Ordovician (?)*: mainly thin-bedded, thixotropically deformed sandstone turbidite and thick-bedded, graded, granular wacke; subordinate psammitic and semi-pelitic schist, pyritiferous spotted hornfels, hornfelsic schist, agmatitic paragneiss, mafic greenschist and

MIDDLE ORDOVICIAN


ROBERTS ARM GROUP

CRESCENT LAKE FORMATION


-  **UNIT 8** - *Early Middle Ordovician (?)*: mainly thick-bedded, epiclast-rich granular wacke and sandstone turbidite; subordinate pebbly wacke and graded microconglomerate;


-  **8A**, thin-bedded red chert, maroon siltstone and laminated green siliceous argillite

CRESCENT BASALTS (?)

-  **UNIT 7** - *Early Middle Ordovician (?)*: mainly amygdaloidal porphyritic basalt, hematitic pillow lava and vesicular pillow breccia; polymict breccia having well-rounded sedimentary, volcanic and hypabyssal clasts; subordinate laminated chert, siliceous argillite, calcareous siltstone and carbonate conglomerate; minor gabbro sills

UNNAMED DIVISIONS OF THE ROBERTS ARM GROUP

-  **UNIT 6A** - *Early Middle Ordovician (?)*: mainly laminated red chert and green siliceous argillite interstratified with medium-bedded, parallel-laminated sandstone turbidite and fine-grained graded siliceous wacke; subordinate unstratified basalt, porphyritic pillow lava and well-bedded pillow breccia; chloritic basalt and epidote-rich breccia transitional to very siliceous rocks having disseminations of jasper, hematite, pyrite and chalcopyrite; brecciated quartz - feldspar porphyry sills and comagmatic gabbro sheets; diabase dykes

-  **UNIT 6B** - *Early Middle Ordovician (?)*: mainly felsic lithic tuff, rhyolite breccia and flow-banded rhyolite; very thick-bedded, poorly sorted, epiclast-rich tuffaceous wacke; subordinate graded crystal tuff and feldspathic sandstone turbidite; minor gabbro sills and pillowed basalt

MIDDLE ORDOVICIAN (?)**GRANITIC ROCKS OF THE ROBERTS ARM GROUP***LOON POND QUARTZ MONZONITE*

UNIT 5 - *Early Middle Ordovician (?)*: mainly biotite quartz monzonite; subordinate quartz-rich, hornblende-biotite granodiorite, biotite porphyritic leucogranite and graphic microgranite; satellite intrusions of quartz-phyric granite and minor aplite dykes

UNNAMED DIVISIONS CONTINUED (BOOT HARBOUR BASALTS ? OF THE ROBERTS ARM GROUP)

UNIT 4 - *Early Middle Ordovician (?)*: mainly regionally silicified basaltic breccia, epidote-rich pillow breccia and poly lithic chloritic tuff; subordinate lenticles of massive rhyolitic breccias, thickly bedded lithic-crystal tuffs and minor flow-layered tuff; altered quartz - feldspar porphyry and local felsite dykes

EARLY ORDOVICIAN**MANSFIELD COVE COMPLEX**

UNIT 3 - *Late Early Ordovician*: equigranular epidote-rich plagiogranite and albite-bearing tonalite; subordinate hornblende - biotite granodiorite, alkali granite and pink aplite; minor diabase dykes and mafic dykelets

EARLY ORDOVICIAN(?)**HALL HILL COMPLEX**

UNIT 2 - *Late Early Ordovician (?)*: equigranular diorite and quartz diorite; subordinate hornblende gabbro; minor diabase

UNIT 1 - *Late Cambrian - Early Ordovician (?)*: equigranular pyroxene gabbro, pyroxenite, leucogabbro and gabbro pegmatite; subordinate amphibolitized gabbro, chloritized amphibolite gneiss, pyritic protoclastic gneiss and well-banded felsic orthogneiss; abundant diabase dyke swarms, common quartz-feldspar porphyry dykes

SYMBOLS

Geological boundary (approximate)	
Reverse fault (barbs in dip direction)	
Transcurrent fault (dextral, sinistral)	
Axial trace of primary anticline (plunge direction indicated)	
Axial trace of primary syncline (plunge direction indicated)	
Axial trace of secondary antiform (plunge direction indicated)	
Axial trace of secondary synform (plunge direction indicated)	

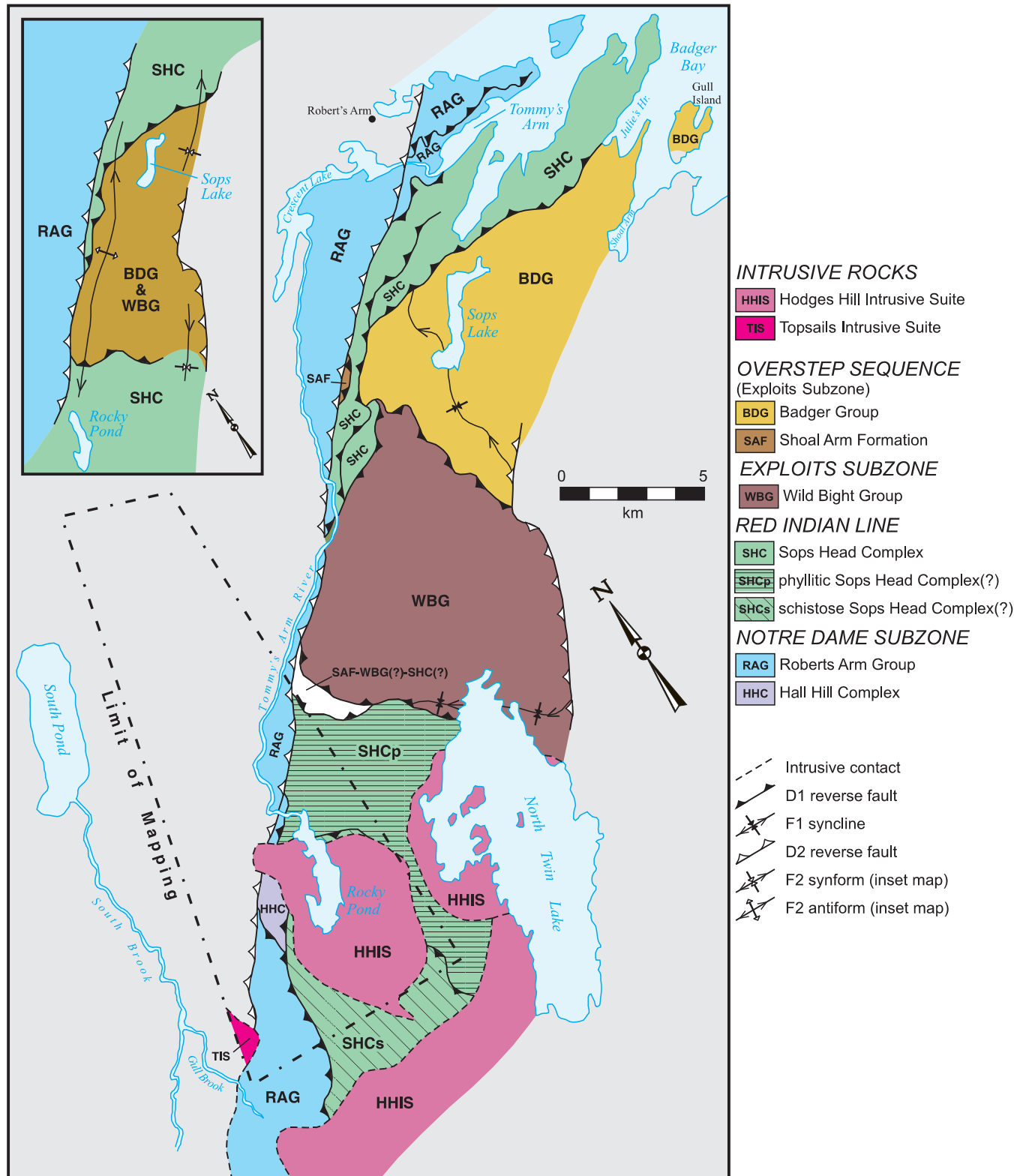


Figure 2. Tectonic setting of the area surveyed in relation to the major structures and regional geological units that define the Red Indian line structural zone near the Tommy's Arm River in western Notre Dame Bay.

base of the global Middle Ordovician series. The duration of the *U. austrodentatus* Zone has been previously estimated to be only 1 to 2 Ma (Huff *et al.*, 1997). O'Brien *et al.* (1997) postulated an approximate 2 My interval that extended from ca. 470 Ma to ca. 468 Ma on the assumption that the base of this biozone lay near the bottom of the Llanvirn (Tucker and McKerrrow, 1995). Moreover, the traditional 'Llandeilo–Llanvirn' boundary was assumed to be ca. 464 Ma, as the *Didymograptus murchisoni* graptolite zone of the Abereiddian stage of the early Llanvirn, which underlies the Llandeilian *H. teretiusculus* Zone and is at least two graptolite biozones above the *U. austrodentatus* Zone, was estimated to be 464.6 ± 1.8 Ma (Tucker and McKerrrow, 1995). Thus, there appears to be a ca. 6 Ma discrepancy between the estimates of the absolute age of the base of the Darriwilian in Newfoundland and in Argentina.

Traditionally, the British Arenig series has been considered to be Early Ordovician and placed below the revised Middle Ordovician Llanvirn series. This has also been the practice in Newfoundland (e.g., O'Brien and Szybinski, 1989). However, by drawing the base of the global Darriwilian stage at the base of the *Undulograptus austrodentatus* graptolite zone and within the *M. flabellum parva* conodont zone (McConnell *et al.*, 2002), the lower part of the British or Scandinavian *Didymograptus hirundo* graptolite zone (the *Isograptus victoriae maximus* to *Undulograptus austrodentatus* biozones of Maletz, 1997) would be removed from the late Early Ordovician (the top Arenig or Fennian stage of Fortey *et al.*, 1995) and placed instead in the lower level of the Middle Ordovician below the Darriwilian.

In the Buchans Group of central Newfoundland, limestone blocks in a rhyolitic breccia dated at $473 \pm 3/-2$ Ma (Dunning and Krogh, 1991) have been interpreted as being synvolcanic and deposited in latest Arenig–earliest Llanvirn time (Nowlan and Thurlow, 1984). The carbonates are reported to contain conodonts correlatable with part of the early Whiterockian *Histiodella holodentata* Zone and are similar to those found in the early Middle Ordovician (early Champlanian) Antelope Valley Limestone of Nevada and the Table Head Group of western Newfoundland (Nowlan and Thurlow, 1984). Lying above the *M. flabellum parva* Zone within the *E. ?variabilis* conodont zone (O'Brien and Szybinski, 1989; Fordham, 1992), some of the youngest reworked limestone blocks contain the conodont *Polonodus* Dzik and are probably equivalent in age to the *Paraglossograptus tentaculatus* Zone (Nowlan and Thurlow, 1984). This is at least one graptolite biozone above the base of the Darriwilian and what most workers would deem to be early Llanvirn in age (e.g., Maletz *et al.*, 1995; Maletz, 1997).

Thus, ca. 471 Ma (the minimum crystallization age of the isotopically dated volcanic rock in the Buchans Group) is the youngest possible age for the top Arenig in Newfoundland (Tucker and McKerrrow, 1995), although this upper limit would include most of the British Fennian stage of the Arenig (Fortey *et al.*, 1995). This is supported by the $469 \pm 5/-3$ Ma age of felsic volcanic rocks (Dunning and Krogh, 1991) in the earliest Llanvirn (early Darriwilian = *U. austrodentatus* Zone and younger) part of the Cutwell Group in western Notre Dame Bay (O'Brien and Szybinski, 1989). Landing *et al.* (1997), who interpreted some of the Buchans Group fauna to be late Arenig in age, considered the fossiliferous limestone blocks to predate the postulated ca. 468 Ma older age limit for the base of the Llanvirn.

Okulitch (2001) considered the base of the Darriwilian to lie near but below the base of Nevada's Middle Ordovician Kanoshian series, which extends from the *H. holodentata* to the *P. aculeata* conodont zones (Fordham, 1992). Also, Okulitch (*ibid*) thought that the base of the Darriwilian was slightly older than the base of the Middle Ordovician Llanvirn, a series that was revised to extend from the *E. ?variabilis* into the *P. anserinus* conodont zones (Fortey *et al.*, 1995). As the age range of such North American and North Atlantic conodont biozones is similar, correlation of these Darriwilian equivalents is facilitated. Hence, the upper Whiterockian of western North America (in part Chazy of eastern North America) is approximately equivalent to the revised Llandeilian and uppermost Abereiddian stages of the Llanvirn, the middle Whiterockian (in part Kanoshian) is approximately equivalent to most of the Abereiddian stage of the Llanvirn and most of the Fennian stage of the late Arenig, and the lower Whiterockian (Rangerian) is approximately equivalent to the lowermost Fennian stage and possibly the upper Whitlandian stage of the revised Arenig series.

In the continental interior of North America, the base of the Rangerian has been traditionally considered as the base of the Middle Ordovician and, as such, has been regionally correlated with the base of the Llanvirn (Abereiddian) in the United Kingdom. The lowermost Rangerian is slightly older than the Rangerian–Kanoshian boundary, which has been provisionally dated at 469 ± 4 Ma (Okulitch, 2001). These data suggest estimates as old as ca. 470 Ma for the base of the Darriwilian (= base of the *U. austrodentatus* Zone = base of a 'Llanvirn' series that includes the Fennian and Rangerian). However, they do imply that the upper part of the global Middle Ordovician stage, which is restricted to the ca. 460–ca. 464 Ma period in the Darriwilian of Argentina (Huff *et al.*, 1997), spans almost all of the 'traditional' Middle Ordovician time interval in Newfoundland (ca. 470 to ca.

458 Ma; top *Pygodus anserinus* conodont zone to bottom *Undulograptus austrodentatus* graptolite zone; see O'Brien and Szybinski, 1989 and O'Brien *et al.*, 1997). In this regard, it is noted that the traditional ('sub-Llandeilo') Llanvirn has been estimated to range from ca. 468 to ca. 464 Ma (Landing *et al.*, 1997).

A likely candidate for the base of the global Middle Ordovician series is the base of the *Tripodis laevis* conodont zone (Finney and Ethington, 2000). Located at the Ibexian–Whiterockian boundary in Nevada, the *T. laevis* (= *T. combsi*) conodont zone is reported from the *Isograptus victoriae lunatus* and the younger *Isograptus victoriae victoriae* graptolite zones (Finney and Ethington, 2000; Mitchell, 2001; Loch, 2002). Both of these biozones underlie the latest Arenigian *Isograptus victoriae maximus* graptolite zone in Newfoundland (Williams *et al.*, 1994; O'Brien *et al.*, 1997). So defined, the base of the Middle Ordovician would straddle the lower Champlanian–upper Canadian series boundary in North America and equate to the *I.c. gibberulus* graptolite zone of the Arenig series of the United Kingdom (upper Whitlandian and lower Fennian stages; mid-late Arenig; Fortey *et al.*, 1995). Thus, to some, the global series boundary between the Middle Ordovician and the Early Ordovician is not coincident with the top of the Arenig, but lies instead within the middle part of that British series (Mitchell, 2001).

Using proposed international terminology, the uppermost part of the Lower Ordovician lies immediately beneath the *Tetragraptus approximatus* graptolite zone (Maletz *et al.*, 1995), which has been postulated to have an absolute age of about 479 Ma (Cooper, 1999). The bottom of the revised British Arenig series (the lowermost Moridunian) is also drawn at the base of the *T. approximatus* Zone (Fortey *et al.*, 1995). The absolute age of certain strata in the lower part of this graptolite biozone is ca. 478 ± 4 Ma (Okulitch, 2001), although estimates as old as ca. 485 Ma have been published for the Early Ordovician base of the Arenig (Tucker and McKerrow, 1995).

In this paper, the base of the Middle Ordovician (the bottom of the lower unnamed stage of the global Middle Ordovician series) is assumed to be ca. 473 Ma, since the absolute age of the *T. laevis* conodont biozone is unknown. This was done by arbitrarily placing the top of the Lower Ordovician in the middle part of the Whitlandian stage of the British Arenig series, well above the *T. approximatus* graptolite zone. This makes the Middle Ordovician about 12 My in duration (ca. 473 to 461 Ma) and the Early Ordovician about 14 My in duration (ca. 488 to 474 Ma).

STRATIGRAPHIC NOMENCLATURE

Espenshade (1937) first recognized the Roberts Arm Volcanics as a mappable unit in the region between Halls Bay and Sops Arm of Badger Bay. He originally assigned the Roberts Arm volcanic rocks and the southeasterly adjacent Crescent Lake shales to the upper part of the Badger Bay Series. This volcano-sedimentary sequence was stated to be in stratigraphic conformity with his Wild Bight–Shoal Arm–Gull Island succession, which comprised the lower part of that series.

Subsequently, Hayes (1951) correlated the red and green shales near Crescent Lake with the red and green argillites that lay conformably below the fossiliferous black shale in the bottom of Shoal Arm. He placed the Crescent Lake Formation stratigraphically above the Gull Island member of his Sansom Formation, as the Gull Island greywacke succession was observed to succeed the Late Ordovician (Caradoc) black shales of the Shoal Arm Formation in the bottom of Badger Bay. Thus, he considered that the unfossiliferous Roberts Arm Volcanics were younger than the purported Late Ordovician Crescent Lake shales, and that the black shale and greywacke units of the lower Badger Bay Series pinched out toward the northwest beneath the Roberts Arm Volcanics.

Williams (1962, 1963) reassigned the Gull Island succession of the Sansom Formation to the upper part of the Exploits Group and positioned such greywackes above the Caradoc black shale and the known Chazyian succession of the Exploits Group. He formally erected the Wild Bight Group and positioned it stratigraphically beneath the local section of the Exploits Group, and placed the structurally overlying Crescent Lake Formation and Roberts Arm Volcanics in a new lithostratigraphic unit named the Roberts Arm Group. However, unlike previous workers, he considered his Roberts Arm Group to be, everywhere, in faulted contact with the redefined Exploits and Wild Bight groups.

Horne and Helwig (1969) emphasized that Ordovician volcanic, plutonic and sedimentary rocks included in the Roberts Arm Group probably faced northwestward in the regional stratigraphic sense. Furthermore, such rocks were thought not to be directly correlatable with the Ordovician volcanic and Ordovician–Silurian sedimentary rocks that lay to the southeast, though some rock types were stated to be remarkably similar. Horne and Helwig (1969) believed that the Roberts Arm Group was restricted to the area northwest of the regional Lukes Arm Fault Zone, which was defined to include the Lukes Arm Fault, the Chanceport

Fault, the Lobster Cove Fault, the Sops Head Fault and the Tommys Arm Fault.

PREVIOUS WORK—REGIONAL GEOLOGY

The regional Lukes Arm–Sops Head Fault Zone (Blewett, 1989) separates the Roberts Arm and Wild Bight groups in the west, the Cottrells Cove and Exploits groups in the centre, and the Chanceport and Summerford groups in the east of Notre Dame Bay. Dean (1978) correlated the Moores Cove Formation of his Cottrells Cove Group with the Crescent Lake Formation (Williams, 1963) of the Roberts Arm Group. The volcanosedimentary rocks of the Cottrells Cove Group are probably Early Ordovician (Tremadoc) and early Middle Ordovician (late Arenig to Llanvirn) in age (Dec *et al.*, 1997; G.S. Nowlan, written communications, 1996, 1997). The early Middle Ordovician Buchans Group occurs along the tectonic strike of the Roberts Arm Group to the southwest (Thurlow and Swanson, 1987; Nowlan and Thurlow, 1984, 1987; Dunning *et al.*, 1987). Volcanic, calcareous and epiclastic strata in the middle–upper part of the Buchans Group (basal Sandy Lake Formation; ca. 473 +3/-2 Ma) have been traditionally correlated with the known earliest Middle Ordovician volcanic rocks (ca. 473 ± 2 Ma) in the northwestern part of the Roberts Arm Group (Kean *et al.*, 1981; Dunning *et al.*, 1987).

Within the western part of the Lukes Arm–Sops Head Fault Zone, Dean (1977) formally erected the Late Ordovician–Early Silurian Sops Head Complex (Figure 2) and included within it various chaotically deformed sedimentary rocks and adjacent partially broken and unbroken formations of volcanic and volcanoclastic strata (including the Julies Harbour and Burtons Head sequences of Espenshade, 1937 and Hayes, 1951). He assigned this mélange-bearing lithostratigraphic unit to the stratigraphically lowest part of the Roberts Arm Group and positioned it immediately beneath the Crescent Lake Formation. The Tommys Arm Fault was shown, for the most part, as forming the southeast boundary of the Roberts Arm Group (and the northwest boundary of the ‘Sansom greywacke’) and its splay, the Sops Head Fault, as forming the southeast boundary of the Sops Head Complex. Post-thrusting dextral transcurrent movements on the Tommys Arm Fault displaced a pluton near Rocky Pond that had tectonically stitched the ‘Sansom greywacke’ and the Roberts Arm Group. Swinden and Sacks (1996) correlated the Rocky Pond pluton with Dean’s Twin Lakes diorite complex, a component of the Hodges Hill Intrusive Suite (Dickson, 2001).

The Boones Point Complex (Helwig, 1969) crops out to the northeast of the Roberts Arm Group adjacent to the Lukes Arm–Sops Head Fault Zone. Dean (1978) originally

placed this mélange-bearing lithostratigraphic unit at the stratigraphic base of the Cottrells Cove Group. Nelson (1981) equated the Sops Head Complex and the Boones Point Complex, recognized sedimentary olistostromes and tectonic block-in-matrix rocks in both units, and presumed that these complexes had formed in the Late Ordovician and Early Silurian.

In several localities southeast of the Tommy’s Arm River, Clarke (1992) established that the section structurally underlying the Roberts Arm basalts and the Crescent Lake shales, and lying tectonically adjacent to the mélange tracts and broken formations of the Sops Head Complex, has a biostratigraphic range extending from the late Caradoc to the early Ashgill (Late Ordovician). Although Williams (1963) placed these graptolite- and conodont-bearing phyl-lites in the Exploits Group, Clarke (1992) reasoned that they were more accurately assigned to the upper part of the Shoal Arm Formation and the lower part of the overlying Badger Group (the Gull Island succession).

Bostock (1988) considered the sedimentary rocks of the basal Crescent Lake Formation of his Middle Ordovician Roberts Arm Group to have once been in depositional contact with a northwesterly adjacent sequence of younger tholeiitic volcanic rocks. In doing so, he accepted the previously postulated stratigraphic positions of map units making up the lower Roberts Arm Group. Moreover, Bostock concluded that the unfossiliferous wackes and tholeiitic basalts of the lower Roberts Arm Group were structurally overlain by higher allochthons that were thrust toward the southeast. These stacked fault-bounded tracts of calc-alkaline volcanic rocks were thought to comprise a series of exotic ‘terrane’s. The upper thrust sheets were stated to contain more abundant felsic pyroclastic rocks than the lower thrust sheets and to generally represent younger, albeit, completely unrelated parts of the Roberts Arm Group.

In the type area along the coast, Kerr (1996) advanced the notion of a detached northwest-directed anticlinal nappe as being the major structure controlling disposition of the Roberts Arm Group. He interpreted the dominantly northwest-facing ‘terrane’s of the Roberts Arm Group as defined by Bostock (1988) to be regionally inverted, each lithotectonic sequence becoming younger downward on passing from southeast to northwest. Thus, the northwestern thrust-fault-bounded panels lay below the southeastern thrust-fault-bounded panels on the imbricated lower fold limb of a recumbent nappe, when the thrust stack was restored to its orientation prior to the Silurian deposition of the Springdale Group (ca. 432 to 425 Ma; Coyle and Strong, 1987).

West of the confluence of Gull Brook and South Brook (Figure 2), terrestrial volcanic rocks, lahars and coarse talus

breccias comprise the lower part of the Springdale Group (Dean, 1977), which has been interpreted to lie nonconformably above the plutonic rocks of the Hall Hill complex (Coyle and Strong, 1987). The Hall Hill complex (Currie, 1976) was defined by Bostock (1988) to include the Rowsell Hill basalt (part of the Lushs Bight Group), the Mansfield Cove plagiogranite (part of the Mansfield Cove Complex), the South Pond gabbro (hosted by the Rowsell Hill basalt and possibly the Mansfield Cove plagiogranite), an unnamed quartz diorite body (northwest of the historic base-metal and gold prospect at Handcamp), and at least one mafic dyke swarm (hosted by the Mansfield Cove plagiogranite).

Bostock (1988) postulated that the plutonic rocks comprising the putative Mansfield Cove–Hall Hill arc–ophiolite complex were much older than, and unrelated to, the volcanic rocks seen in the Roberts Arm Group. In contrast, Swinden (1987) thought that some calc-alkaline volcanic rock sequences in the northwestern part of the Roberts Arm Group (Middle Ordovician; ca. 473 Ma; Dunning *et al.*, 1987) had possibly been erupted above slightly older arc plutonic rocks (Early Ordovician; ca. 479 Ma Mansfield Cove plagiogranite; Dunning *et al.*, 1987). However, a regional structure termed the Mansfield Cove Fault was thought to have juxtaposed the Hall Hill complex and the Roberts Arm Group.

ROBERTS ARM GROUP

LITHOLOGICAL SUBDIVISIONS OF STRATIFIED ROCKS

In the area surveyed, the early Middle Ordovician strata of the Roberts Arm Group are divisible into several lithologically distinct units whose distribution can be depicted on regional geological maps (Units 4, 6, 7, 8; Figure 1). These comprise unnamed divisions of mainly mafic and lesser felsic volcanic rocks, bimodal volcanic and siliciclastic sedimentary rocks, and dominantly mafic volcanic and minor carbonate rocks. In two places, in the easternmost part of the map area, a coarsening-upward sequence of epiclastic to polymictic sedimentary rocks is present northwest of the Tommys Arm Fault. Together, these map units represent the inland continuation of parts of the original Roberts Arm Volcanics and the Crescent Lake Formation.

Rocks in Unit 4 probably represent a southwesterly strike extension of part of the Boot Harbour tectonic panel of the Roberts Arm Group (Kerr, 1996; Figure 1). Northwest of the town of Robert's Arm, the Boot Harbour sequence contains pillow basalt, andesite and intercalated lenticles of felsic volcanic rocks that were previously dated at 473 ± 2 Ma (Dunning *et al.*, 1987). In the area surveyed, pyroclastic

and hypabyssal igneous rocks make up most of Unit 4; sedimentary rocks are conspicuously absent.

The dominant rock types in Unit 4 are silicified basaltic breccia and chloritized mafic agglomerate. In some localities, these rocks are observed to overlie pillow breccia. In places, strongly epidotized mafic tuffs display angular clasts of red chert and several different textural types of basalt. The felsic volcanic rocks in Unit 4 form small discontinuous lenticles within the mafic pyroclastic succession. Massive rhyolitic breccias and lithic–crystal tuffs marked by outsized felsic lapilli clasts are interstratified with less common flow-layered quartz–feldspar crystal tuff. Abundant quartz–feldspar porphyry dykes, which are altered to form saussurite, sericite and pyrite aggregates, crosscut the mafic and felsic pyroclastic strata of Unit 4.

Unit 6 of the Roberts Arm Group is restricted to the southwestern part of the map area (Figure 1). It comprises an internally faulted and complexly folded sequence of bimodal volcanic and sedimentary rocks. The western portion of Unit 6 (Unit 6a) mainly consists of mafic lavas intercalated with fine-grained siliciclastic and chemical sedimentary rocks. Near the historic Handcamp base-metal prospect, in the southeastern part of this subunit, variably chloritized basalt and epidotized pillow breccia are seen to be in transitional contact with light grey and pink, very siliceous, net-veined, mafic volcanic rocks. This stockwork zone, which appears to lie below most of the tightly folded sedimentary sequences, has disseminations of jasper, hematite, pyrite and chalcopyrite.

The central part of Unit 6a is mostly underlain by thin-bedded and laminated red chert interstratified with medium-bedded, grey and green, fine-grained wacke and graded sandstone turbidite. Minor lenticles of red and green, siliceous argillite and light grey, thin-bedded, parallel-laminated sandstone separate pillow basalt intervals. Widespread gabbro sheets, abundant quartz–feldspar porphyry sills and rare diabase dykes intrude the sedimentary and volcanic strata. In places, altered quartz-porphyrific felsic dykes display localized quartz stringers and internal zones of quartz-cemented breccia. Porphyritic pillow lava interstratified with pillow breccia predominates in the western part of Unit 6a, although massive to thickly-stratified flow sheets of dark grey and light green basalt are found structurally beneath the Hall Hill complex.

The eastern portion of Unit 6 of the Roberts Arm Group (Unit 6b) is mainly composed of felsic pyroclastic and epiclastic sedimentary rocks (Figure 1). From southeast to northwest, this subunit contains subordinate pillow breccia and pillowed basalt, a lenticle of light grey, very thick-bedded, poorly sorted, coarse-grained volcanoclastic wacke

interstratified with graded, quartz- and feldspar-rich sandstone turbidite, a prominent tract of felsic lithic tuff and rhyolitic breccia, and lesser crystal-lithic tuff having outsized clasts of felsic and mafic volcanic rocks. Gabbro sills seem to have been preferentially emplaced near the epiclastic sedimentary rocks but they represent a minor constituent of Unit 6b.

Strata in Unit 7 represent the southwestern extension of a distinctive trace of mafic volcanic rocks that have previously been assigned to the Crescent 'terrane' of the Roberts Arm Group (Bostock, 1988; Kerr, 1996). Mostly outcropping in the northeast of the map area (Figure 1), the unit generally consists of hematitic pillow lava with red interstitial chert and carbonate-cemented pillow breccia in common association with interflow limestone. Unit 7 contains several fault-bounded homoclinal successions of basalt flows, one of which is located to the west of Loon Pond structurally beneath the Hall Hill plagiogranite (Figure 1).

Immediately northwest of the Tommys Arm Fault, porphyroblastic schist, actinolite schist and chlorite schist pass upward into amygdaloidal porphyritic basalt and vesicular pillow lava assigned to Unit 7. In places, chloritized basaltic breccias preserve rip-up clasts of red siliceous argillite. Farther northwest, the succession includes carbonate conglomerate and epiclastic breccias having well-rounded, coarse-grained clasts of hematized basalt, red chert and diabase. Minor interbedded intervals of green and red wacke, graded sandstone turbidite, dark-grey laminated chert and green siliceous argillite are also present. All of these sedimentary and volcanic rocks are intruded by subordinate gabbro sills.

Rocks in the northernmost part of Unit 7 are interpreted to stratigraphically underlie the Crescent Lake Formation (Figure 1). This portion of Unit 7 consists of dark-grey pillowed basalts, dark-green vesicular pillow breccias, and reddish-green hematitic basalts. Located between such mafic flow units are variably thick intervals of chloritic mafic tuff with interstitial green siliceous argillite, red chert and siltstone interbeds, minor carbonate lenses and rare calcareous siltstones.

In the area surveyed, the Crescent Lake Formation of the Roberts Arm Group is represented by sedimentary strata assigned to Unit 8 (Figure 1). The northern tract of Unit 8 probably contains the lower part of the Crescent Lake Formation; whereas, the southern tract is thought to preserve some of the upper part of that formation. On the basis of the correlation with the Moores Cove Formation, the Crescent Lake Formation is presumed to be early Middle Ordovician (latest Arenig to Llanvirn).

East of Loon Pond (Figure 1), Unit 8 is composed of thinly interbedded, maroon argillite and red chert together with dark-red, parallel-laminated siliceous argillite and dark-green, thin-bedded, crosslaminated siltstone. Higher in the succession, light-green, thin-bedded sandstone turbidites are intercalated with these marine red beds. This subunit is well developed immediately east of the map area near the lower reaches of the Tommy's Arm River, west of Kippens Pond.

In the fault-bounded tectonic panel north of Rocky Pond (Figure 1), the sedimentary strata of Unit 8 are coarser grained and more thickly stratified. Here, dark-green, thin- to thick-bedded granular wackes commonly illustrate sharp or erosive bases and display angular rip-up clasts of green laminated argillite. Many graded beds of pebbly wacke have a basal microconglomeratic lag, which contains well-rounded detrital clasts of orange jasper, red chert and green basalt. In a few localities, in the southeasternmost part of Unit 8 near the Tommys Arm Fault, the dominantly basalt-rich green turbidites are observed to be interstratified with relatively quartz-rich grey turbidites.

GRANITIC ROCKS

Several shallow-level granitic plutons and small sub-volcanic bosses have been previously mapped within the outcrop of the stratified rocks of the Roberts Arm Group and have been assumed to be Middle Ordovician in age (Bostock, 1988). In the map area, the Loon Pond pluton was shown to intrude the calc-alkaline volcanic rocks of the Boot Harbour 'terrane' as well as the tholeiitic volcanic rocks lying adjacent to the Crescent Lake Formation. In places, the pluton was also shown to be in fault contact with the country rocks. Bostock (1988) reasoned that microgranitic and felsite magmas feeding the plutonic body were emplaced at very high crustal levels. Intrusion was thought to have occurred during or after the structural inversion of kilometre-sized slump blocks, some made up of thick successions of pillowed tholeiite (Crescent 'terrane').

The Loon Pond pluton forms a northwest- and northeast-trending sheet that is about 8 km long but varies from 0.1 km to 2 km wide (Unit 5, Figure 1). Tapered to the north and south, it is composed of a western belt of medium-grained intermediate plutonic rocks and an eastern belt of mainly fine-grained felsic plutonic rocks. Both belts of plutonic rocks are observed to intrude the mafic and felsic pyroclastic rocks of Unit 4 of the Roberts Arm Group. Light green and pinkish grey, quartz-rich, hornblende-biotite granodiorite and light grey, equigranular, biotite quartz monzonite predominate in the western part of the area surveyed.

Buff biotite–porphyritic leucogranite, pink graphic microgranite and aplite dykes are more abundant in the east of the map area.

In several places, medium-grained quartz monzonite is extensively saussuritized, locally silicified and crosscut by fresh aplite. In one locality at the northeast margin of the pluton, sericitic microgranite and an associated chloritic intrusive breccia contain pyrite and chalcopyrite disseminations and are crosscut by fresh gabbro. Along its southeast margin, thin quartz-phyric granite sheets form abundant satellite intrusions in Unit 4 pyroclastic rocks of the Roberts Arm Group. The Loon Pond pluton could be interpreted as a sill complex with its western margin representing the bottom and its east side forming the top of the sheeted intrusion. This is consistent with the bulk of the stratigraphic top determinations in Unit 4 host rocks.

Although the Loon Pond pluton was systematically mapped, an intrusive relationship with the Hall Hill complex could not be confirmed (Swinden, 1987). In the shallow subsurface of the map area, the granitic intrusion probably lies in fault contact with Unit 7 of the Roberts Arm Group. Likewise, southwest of section line AA' (Figure 1), the Unit 5 pluton could possibly be directly tectonically juxtaposed with Unit 1 of the Hall Hill complex as, at surface, only 25 m of Unit 4 volcanic rocks separate quartz monzonite from sheared metagabbro. It is likely that the plutonic rocks near Loon Pond are no older than the Boot Harbour volcanic rocks (ca. 473 Ma ?) and no younger than the sedimentary rocks of the Crescent Lake Formation (earliest Llanvirn; ca. 469 Ma ?), because the widespread alteration in Units 4 and 5 is not seen in Units 7 and 8.

STRUCTURAL AND STRATIGRAPHIC RELATIONSHIPS

In cross section AA' (Figure 3), the generally southeast-facing rocks of Unit 4 are shown to be up-faulted toward the southeast and placed above an inverted southeast-facing succession of Unit 7. The immediate footwall sequence is thought to be positioned near the stratigraphic top of Unit 7 and, farther southeast, is believed to contain a footwall syncline cored by the Crescent Lake Formation (Unit 8). A right-way-up, northwest-facing tectonic slice of Unit 7, which probably occurs lower in the stratigraphic section, occurs to the northwest of Unit 4. Directly underlying the Mansfield Cove Fault, this tectonic slice of Unit 7 locally separates Unit 4 from the structurally overlying Hall Hill and Mansfield Cove complexes.

Thus, the pyroclastic rocks of Unit 4 and the plutonic rocks of Unit 5 probably outcrop in a 'faulted anticlinorium' in the calc-alkaline belt of the Roberts Arm Group, flanked

by disrupted sequences of the Crescent tholeiite 'terrane'. Although an anticline does not close within Unit 4 or Unit 7, it is the distribution of the faulted right-way-up and inverted tracts of Unit 7 relative to the intervening rocks in Unit 4 that underscores the simplified notion of a regional 'anticlinorium'. The geometry is similar to that of structures controlling the distribution of the Fortune Harbour Formation and the Moores Cove Formation of the Cottrells Cove Group in the footwall of the Chanceport Fault (Dec *et al.*, 1997).

Farther southwest, Unit 4 remains in the hanging wall of a regional southeast-directed reverse fault, although the structural thickness of the southeast-facing strata comprising the map unit is significantly decreased (*see* cross section BB' in Figure 3). A northwest-facing homoclinal sequence of Unit 7 volcanic rocks occurs in the footwall of this folded reverse fault (as the syncline disposing Units 7 and 8 is excised between AA' and BB'). In the valley of the Tommy's Arm River, this sequence is itself faulted above a southeasterly adjacent tract of Unit 8 sedimentary strata. That part of the Crescent Lake Formation preserved in the southern tract of Unit 8 ranges from an interval of red siliceous argillite and green laminated siltstone upward to an interval of green turbidite and pebbly wacke, notable for its conspicuous clasts of jasper, chert, granite and basalt. This stratigraphic section is observable along the east bank of the Tommy's Arm River, proceeding southwestward toward the headwaters of that river, and it is disposed along the fold axial trace of a regional, fault-bounded, southwest-plunging anticline (BB' in Figure 3).

Proceeding farther southwest, the metamorphic grade begins to increase along a major southeast-directed thrust and reverse fault (CC' in Figure 3). In the vicinity of Rocky Pond, this structure is located directly above Unit 9, the lowermost unbroken formation of the Sops Head Complex (McConnell *et al.*, 2002). Grey pyritic turbidites in this map unit are disposed about a southeasterly overturned footwall syncline and are locally inverted beneath the structurally overlying strata of the Roberts Arm Group. A tectonic constituent of a ductile imbricate fault zone offset by the transcurrent Tommys Arm Fault, the synmetamorphic thrust is responsible for structural termination of the Crescent Lake Formation in the Loon Pond–Rocky Pond area (Figure 1).

The reverse fault, which separates the southeast-facing pyroclastic rocks of Unit 4 and the northwest-facing basalts of Unit 7, is interpreted to have merged with the underlying synmetamorphic sole thrust of the Roberts Arm Group near section line CC'. In doing so, Unit 7 metabasites are tectonically excised in the hanging-wall sequence of the sole thrust and Unit 4 meta-tuffs come in direct juxtaposition with the underlying phyllitic turbidites and porphyroblastic schists

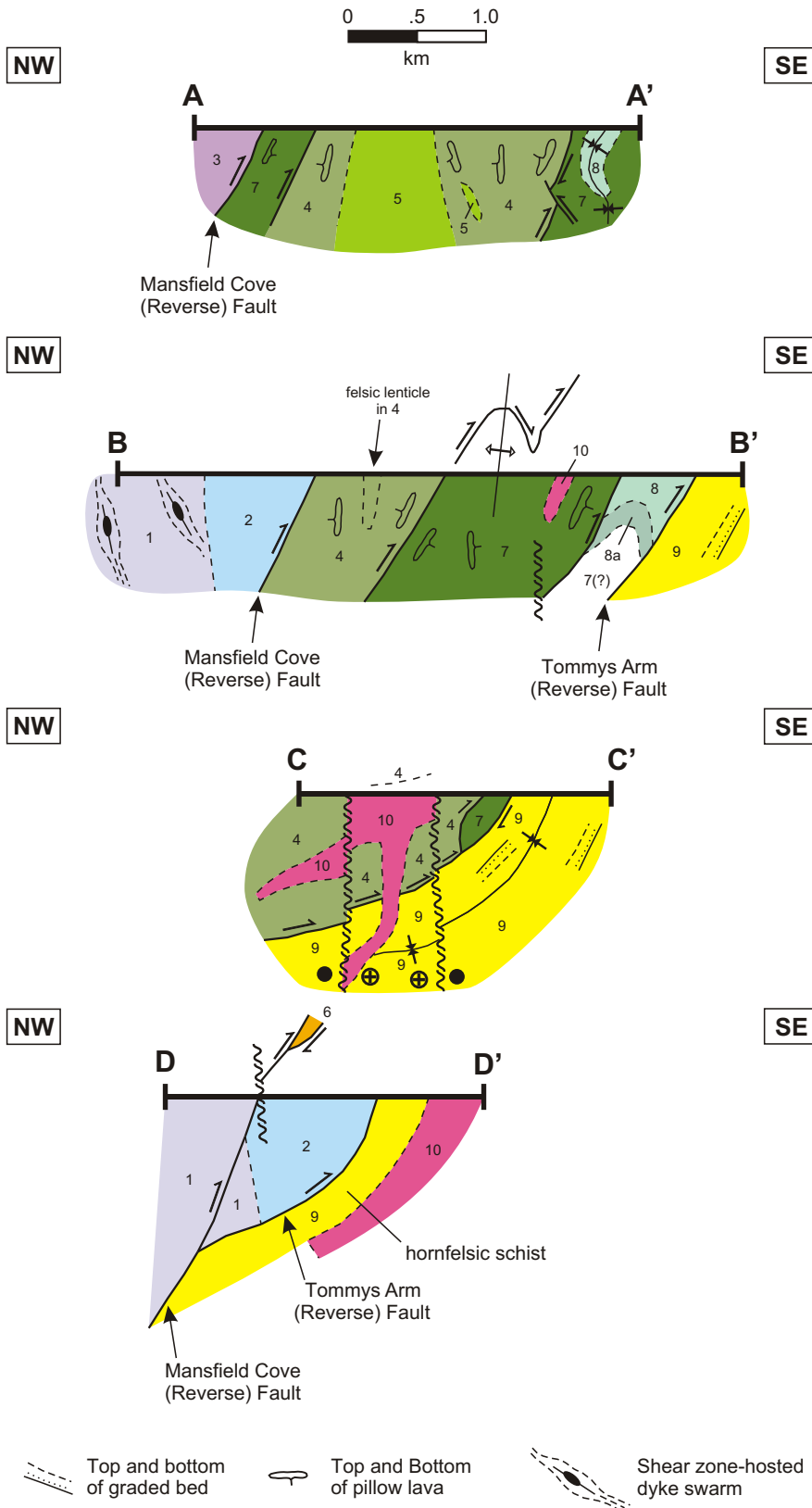


Figure 3. Representative geological cross sections of the Loon Pond–Rocky Pond map area. See Figure 1 for location of section lines AA', BB', CC' and DD'. Symbols as for Figure 1. Vertical scale of unbalanced sections is exaggerated.

found in Unit 9. At this location, the regionally extensive Crescent tholeiite 'terrane' is absent from the lithotectonic sequence of the Roberts Arm Group that rests above the Sops Head Complex.

West of Rocky Pond (Figure 1), the regional fault beneath the Hall Hill complex (the Mansfield Cove reverse fault) is mapped to locally coalesce with the regional fault above the Sops Head Complex (the Tommys Arm reverse fault). Small imbricate splay faults link the regional hanging-wall and footwall sequences of the tectonically telescoped Roberts Arm Group. Near section line DD', Unit 2 of the Hall Hill complex is mapped to directly overthrust a sequence of hornfelsic metasedimentary schists (Unit 9) that are thought to belong to the Sops Head Complex (Figure 3). There, the entire Roberts Arm Group is missing.

Southwest of section line DD', and the regional culmination of the Roberts Arm Group, another structural wedge of Roberts Arm strata crops out between the Hall Hill complex and the Sops Head Complex (Figure 1). A lithotectonic sequence of various sedimentary and bimodal volcanic rocks, Unit 6 is lithostratigraphically discrete, internally faulted and restricted to the southwestern part of the map area.

The tectonic stack of thrusts and nappes at Gullbridge (Calon and Pope, 1990) widens to the southwest and southeast of this past-producing base-metal mine but it narrows considerably northeastward (Dickson, 2001). However, it is possible that Unit 6a of the Roberts Arm Group may represent a part of the Gullbridge bimodal unit and the Gull Pond basalt; whereas, a younger unit called the Eastern Felsic Tuff may reside within Unit 6b (Pudifin, 1993). The Handcamp gold prospect (Evans, 1996) is situated near the reverse fault separating Unit 6a and Unit 6b (Figure 1).

EASTERN HALL HILL COMPLEX

In the area surveyed, the Hall Hill complex and the Mansfield Cove Complex comprise at least three regionally extensive divisions of Early Ordovician and older (?) plutonic rocks (Figure 1). Unit 1 of the Hall Hill complex is mainly composed of coarse-grained gabbro and pyroxenite, Unit 2 of the Hall Hill complex consists of fine-grained diorite and quartz diorite, and Unit 3 (part of the Mansfield Cove Complex) is mainly made up of medium-grained plagiogranite and granodiorite. Along the eastern margin of these complexes, many of the intrusive contacts of the plutonic map units trend at high angles to the Mansfield Cove Fault. Based on their map pattern (Figure 1), all of the constituent units appear to be truncated, in one place or another, by this through-going fault structure. In this regard, the complexes' rock types and their outcrop pattern is similar to that of the fault-bounded Cambro-Ordovician South Lake Igneous Complex (Bostock, 1988; MacLachlan, 1998).

UNIT 1 GABBRO

In many places, the dark-grey, coarse-grained, equigranular, pyroxene gabbro typical of Unit 1 is fresh and undeformed. It is commonly observed to grade to a plagioclase-rich leucogabbro, which displays diffuse pods and veins of coarser gabbroic pegmatite. In other locations, less common amphibolitized gabbro, epidotized amphibolite gneiss, and well-banded felsic orthogneiss have been assigned to Unit 1 of the Hall Hill complex. Northwest- and northeast-trending swarms of diabase dykes form the most widespread suite of minor intrusions in Unit 1. They are present in both the mafic plutonic rocks and the mafic gneisses. Quartz-feldspar porphyry dyke swarms are associated with some of the mafic dyke swarms. Medium-grained diorite sheets that crosscut coarse-grained pyroxene gabbro are seen to pass transitionally into diabasic-textured rocks near the margins of these intrusions. These small diorite bodies have also been tentatively grouped in Unit 1.

In the eastern part of the Hall Hill complex, the foliation in Unit 1 gabbro dips steeply or moderately toward the northeast, the southwest and the northwest. Schistose and gneissose zones within the sheared or platy parts of Unit 1 trend northwestward and northeastward on local and regional scales, as do the swarms of mafic and felsic minor intrusions. In some locations, these shear zone-hosted dyke swarms are crosscut by posttectonic diorite bosses that comprise parts of Unit 2 (see cross section BB' in Figure 3).

The intrusion of quartz-feldspar porphyry dykes within Unit 1 metagabbro bodies is generally predated and postdated by the intrusion of diabase dykes. Typically, several one-sided diabase dykes within a northwest-trending shear zone

are concordantly intruded by a two-sided dyke of quartz-feldspar porphyry and a later diabase. Characteristically, in adjacent swarms of northeast-trending dykes, the foliation in country-rock metagabbro is highly oblique to the minor intrusions. There, quartz-feldspar porphyry dykes are intruded by one-sided diabase dykes that display a north-east-trending internal foliation.

In mylonitized parts of the eastern Hall Hill complex, a well-banded, light- and dark-grey, locally pyritic protoclasic gneiss is cut by isoclinally folded quartz veins and pink microgranite stringers. In places, the protolith of the host protoclasic gneiss seems to be a sheeted mafic-felsic orthogneiss in which relict quartz-feldspar and diabase porphyry textures can still be distinguished. In at least one locality along the Mansfield Cove Fault, porphyroclastic orthogneiss of the Hall Hill complex lies tectonically adjacent to a highly deformed, mineralized, felsic pyroclastic unit assigned to the Roberts Arm Group (Swinden, 1987).

UNIT 2 DIORITE

This division of the Hall Hill complex (Figure 1) includes the South Lake diorite of Bostock (1988) and similar rocks farther south (cross section DD' in Figure 3). The main rock types are equigranular, fine-grained, dark-grey diorite, minor light-grey quartz diorite and rare medium-grained hornblende gabbro. Diorite bodies belonging to Unit 2 crosscut the variably sheared gabbro assigned to Unit 1. They probably come in direct contact with the Rowsell Hill sequence of pillowed basalt, which is elsewhere intruded by Unit 1.

UNIT 3 PLAGIOGRANITE

This division of the Mansfield Cove Complex is restricted to the northern part of the Loon Pond-Rocky Pond area (Figure 1). It includes the Mansfield Cove plagiogranite of Bostock (1988), which has been dated at 479 ± 3 Ma in the area surveyed for this report (Dunning *et al.*, 1987). This part of Unit 3 may be younger than or coeval with some of the diorites found in Unit 2.

The main rock types in Unit 3 are a light-grey equigranular plagiogranite and a light-pink porphyritic tonalite. Locally, these rocks are albitized and epidotized. Subordinate rock types include light grey hornblende-biotite granodiorite and light pink alkali granite, both cut by pink aplite veins. The plagiogranite, tonalite and granodiorite contain abundant diabase dykes intruded by smaller mafic dykelets. Emplaced along epidote-lined fractures in the host plutonic rocks of Unit 3, they constitute one of the youngest dyke swarms in the Hall Hill complex.

WESTERN SOPS HEAD COMPLEX

In the region immediately northeast of the Loon Pond–Rocky Pond map area, the late Early Ordovician and early to late Middle Ordovician Sops Head Complex can be divided into a lower sequence of unbroken lithostratigraphic units, an intervening assemblage of partially broken strata and broken olistostromal units, and an upper unit of tectonized block-in-matrix *mélange* that structurally underlies the Roberts Arm Group (McConnell *et al.*, 2002). The unbroken siliciclastic turbidite formations are thought to be Arenig, the partially broken epiclastic and olistostromal strata are believed to be Llanvirn and Llandeilo, and the tectonic *mélange* tract is assumed to have formed in Silurian or later time. In the type area, the Sops Head Complex is thrust above fossiliferous Ashgillian strata (Clarke, 1992) belonging to the Late Ordovician Gull Island Formation of the Badger Group.

In the area surveyed, Unit 9 is mostly made up of grey siliciclastic turbidites and metasedimentary rocks tentatively correlated with the lowermost unbroken formations of the Sops Head Complex. The main rock types are light-grey, thin-bedded, thixotropically deformed, variably silicified sandstone turbidite interstratified with light-grey, massive and thick-bedded granular wacke. Graded beds of pebble microconglomerate within these turbidites have well-rounded detrital clasts of quartz and feldspar but display minor volcanic or sedimentary clasts.

In the northeastern part of Unit 9, rare interbeds of dark-grey, siliceous laminated siltstone and light-grey siliceous wacke occur in association with very rare horizons of dark-grey pyritic siltstone, basaltic breccia and gabbro sills. In the area surveyed, they are not observed in contact with the grey sandstone turbidites that comprise the majority of Unit 9. However, such strata are lithologically similar to some of the unbroken sedimentary and tectonized olistostromal rocks that are seen to structurally underlie the upper Wild Bight Group on the northwest shore of North Twin Lake (O'Brien, 2001).

METAMORPHIC ROCKS

In the area southwest of the termination of the Crescent Lake Formation of the Roberts Arm Group (Figure 1), the phyllitic turbidite belt of the Sops Head Complex appears to pass gradationally into spotted hornfels and hornfelsic schist and is probably faulted against a regionally extensive belt of metasedimentary gneiss that includes some mafic green-schist and amphibolite (Figure 2; *see also* Swinden, 1987; Swinden and Sacks, 1996; Dickson, 2001). The psammitic muscovite schist and semi-pelitic biotite schist found in Unit 9 commonly contain calc-silicate layers and deformed nod-

ules. Locally, gossans composed of pyritiferous spotted hornfels lie adjacent to the schist and gneiss belt of the Sops Head Complex. In the southwestern part of the map area, these metasedimentary rocks are hornfelsed by sheet intrusions of a weakly to strongly foliated metagabbro. There, a minor amount of sulphidic semi-pelitic and pelitic schist is interlayered with sheared amphibolite and actinolite schist. In one place, a boudinaged lineated paragneiss, which displays relict isoclinal folds of granite veins, quartz lites and a bed-parallel foliation, is locally observed to pass into straightened gneiss that shows incipient agmatite zones.

Although the intensity of deformation and the grade of metamorphism increase westward toward the Tommys Arm thrust and reverse fault (*see* cross sections CC' and DD' in Figure 3), the zone of thermal metamorphism is much wider than the zone of high-strain deformation. In the area surveyed, the thermal and strain gradients are not everywhere coincident nor are they developed to the same extent. The strain gradient in the Sops Head Complex is the dominant tectonic feature northeast of Rocky Pond, where it is developed over a distance of 0.5 km or less. In contrast, the metamorphic gradient is developed over at least 5 km and it is the most obvious geological feature of rocks southwest of that pond. The structural thicknesses of Sops Head rocks affected by the strain and metamorphic gradients are unknown; however, their surface dimensions probably represent an overestimate as porphyroblast-bearing tectonites dip gently southwestward in many locations.

POSTTECTONIC PLUTONIC ROCKS

Two, undated, posttectonic intrusive bodies crosscut the deformed and metamorphosed rocks of the Roberts Arm Group, the Hall Hill complex and the Sops Head Complex in the southern part of the Loon Pond–Rocky Pond area (Figure 1). The Gull Brook pluton (Unit 11) is mapped to cross the folded Mansfield Cove reverse fault. Although it is observed to be emplaced into Unit 1 of the Hall Hill complex, this pluton is inferred to intrude Unit 6a of the Roberts Arm Group. The Rocky Pond pluton (Unit 10) crosscuts the synmetamorphic Tommys Arm reverse fault, and it is observed to be emplaced into Unit 7 of the Roberts Arm Group and Unit 9 of the Sops Head Complex. In places, Unit 10 is assumed to also have originally intruded Unit 2 of the Hall Hill complex and Unit 4 of the Roberts Arm Group, although some of these map unit boundaries are later faults (Figure 3).

Gull Brook Pluton

Unit 11 is mainly composed of pale red, medium- to coarse-grained, equigranular, potassium feldspar-bearing syenite and quartz-rich, hornblende-bearing granite. The

pluton is thought to belong to the Topsails Intrusive Suite, which includes a variety of deformed and undeformed Silurian and Devonian plutons (Whelan and Currie, 1988; Whelan *et al.*, 1996). Dean (1977) reported that the Gull Pond pluton lay nonconformably beneath a cover of Carboniferous red beds immediately west of the map area in the valley of South Brook. Correlative Topsail-type intrusions were stated to crosscut the folded terrestrial strata of the Springdale Group as well as adjacent Ordovician strata.

Rocky Pond Pluton

Unit 10 is predominantly composed of a central granodiorite phase and a more restricted marginal phase of diorite porphyry. The Rocky Pond pluton has been previously postulated to be an extension of the Twin Lakes diorite complex (Dean, 1977; Swinden, 1987). This complex has been included as a constituent of the Early–Late Silurian Hodges Hill Intrusive Suite (Dickson, 2001), and has probably intruded the adjacent Middle Ordovician Mary Ann Granite (ca. 463 ± 6/–4 Ma; G.R. Dunning, unpublished data, 1999).

In the central and eastern parts of the Rocky Pond pluton, a widespread, light-grey, isotropic, equigranular, biotite–hornblende granodiorite displays localized trains of cognate xenoliths. In a few locations, this granodiorite crosscuts and locally separates septa of equigranular gabbro and porphyritic diorite. A well-jointed, hornblende–porphyritic quartz diorite and an associated suite of younger porphyritic mafic dykes occur along most of the southwestern margin of the pluton. Between this area and the Tommys Arm Fault, marginal sheets of gabbro, granodiorite, granite and aplite are widely developed in the metamorphic rocks of the Sops Head Complex.

Where the margin of the Rocky Pond pluton trends northwestward, unfoliated bodies of quartz diorite and granodiorite are mapped to crosscut northeast-trending reverse faults as well as allied folds with axial planar slaty cleavage (Figure 1). However, in several locations, Unit 10 granodiorite is seen to be emplaced into a variably deformed zone of spotted hornfels and porphyroblastic schist. There, in the lower grade rocks, poorly lineated cordierites are augened by a downward-facing phyllitic cleavage. In higher grade rocks, near pre-granodiorite gabbro sheets, randomly oriented amphiboles overgrow a bedding-parallel composite biotite schistosity that augens garnet porphyroblasts. Although spotted cordierites are observed to be randomly oriented on some bedding planes in the phyllite–outer hornfels transition, it is unclear whether such rocks occur in the posttectonic thermal aureole of the Rocky Pond granodiorite.

The Rocky Pond pluton is displaced by a relatively late stage system of conjugate strike-slip faults, which also accommodate some vertical uplift (Figure 1; CC' in Figure 3). Fault movements produced narrow zones of random-fabric cataclastite and silica-cemented gouge. These fault rocks display highly veined fragments of silicified granodiorite and retrograded hornfelsic schist. Near the northern termination of Unit 10, chloritized granodiorite and hornfelsed host rocks are injected by subvertical quartz–chlorite–carbonate vein arrays. These have a predominant northwest and a subordinate northeast trend. A satellite body of marginally net-veined and schistose quartz tonalite, which is hosted by Roberts Arm basalt in the imbricate thrust stack above the Sops Head Complex, is located along strike of one of the northeast-trending transcurrent faults (Figure 1).

CONCLUSIONS

In the Loon Pond–Rocky Pond area, the Ordovician Roberts Arm Group comprises a fault-bounded, internally imbricated and multiple-folded sequence of alternating northwest-facing and southeast-facing volcanosedimentary rocks. Since all stratified rock units are laterally discontinuous, and none of them can be mapped throughout the entire area surveyed, the original depositional order of Units 4, 6 and 7 is not locally discernible.

In exposures of the Roberts Arm Group to the north of Rocky Pond, Crescent 'terrane' tholeiites (Unit 7) are postulated to structurally overlie the pyroclastic volcanic rocks of Unit 4 and the granitic rocks of Unit 5. In contrast, the basal sedimentary rocks of the Crescent Lake Formation (Unit 8) are held to stratigraphically overlie the Unit 7 basalt succession.

In exposures of the Roberts Arm Group to the southwest of Rocky Pond, fine-grained reworked pyroclastic and chemical sedimentary rocks are present within Unit 6. These are completely absent in Unit 4 and they are quite different from the dominantly polymictic and well-rounded epiclastic rocks in Unit 8. In addition, the relative abundance of felsic volcanic flow rocks and composite quartz–feldspar porphyry–gabbro sills, together with the absence of subvolcanic granitic rocks and the lack of ubiquitous alteration of mafic-dominant fragmental rocks, distinguishes the volcanic sequences within Unit 6 from the volcanic rocks of Unit 4.

Thus, two discrete tracts of volcanic and sedimentary rocks, which are both assigned to the Ordovician Roberts Arm Group, terminate within the map area. One probably comprises the southwesternmost part of the coastal belt (Bostock, 1988; Kerr, 1996; Thurlow, 1996); whereas, the

other probably belongs to the northeasternmost extension of the Great Gull Lake belt (Calon and Pope, 1990; Pope *et al.*, 1990; Swinden and Sacks, 1996; Dickson, 2000, 2001). These tracts are separated from each other by a regional tectonic culmination. There, the Roberts Arm Group is totally missing from the lithotectonic sequence of bottom Arenig (ca. 479 Ma; Early Ordovician) to top Llandeilo (ca. 460 Ma; late Darriwilian; Middle Ordovician) rock units that are preserved in the Loon Pond–Rocky Pond–Kippens Pond area (O'Brien, 2001).

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REFERENCES

- Blewett, R.S.
1989: The chronology and kinematics of deformation in the Lower Paleozoic of north-central Newfoundland. Unpublished Ph. D. thesis, University of Leicester, United Kingdom; 204 pages.
- Bostock, H.H.
1988: Geology and petrochemistry of the Ordovician volcano-plutonic Robert's Arm Group, Notre Dame Bay, Newfoundland. Geological Survey of Canada, Bulletin 369, 84 pages.
- Calon, T.J. and Pope, A.J.
1990: A stratigraphic and structural analysis of the Gull-bridge property, central Newfoundland. Internal report for Rio Algom Exploration Inc., Centre for Earth Resources Research, Memorial University, St. John's, Newfoundland, 81 pages.
- Clarke, E.J.
1992: Tectonostratigraphic development and economic geology of the Sops Head Complex, western Notre Dame Bay, Newfoundland. Unpublished B.Sc. (Honours) thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 102 pages.
- Cooper, R.A.
1999: The Ordovician time scale - calibration of graptolite and conodont zones. *In* Quo Vidas Ordovician? Short Papers of the 8th International Symposium on the Ordovician System (Prague, 1999). *Edited by* P. Kraft and O. Fatka. Acta Universitatis Carolinae, Geologica, Volume 43, pages 1-4.
- Cooper, R.A. and Nowlan, G.S.
1999: Proposed global stratotype section and point for base of the Ordovician System. *In* Quo Vidas Ordovician? Short Papers of the 8th International Symposium on the Ordovician System (Prague, 1999). *Edited by* P. Kraft and O. Fatka. Acta Universitatis Carolinae, Geologica, Volume 43, pages 61-64.
- Coyle, M. and Strong, D.F.
1987: Geology of the Springdale Group: a newly recognized Silurian epicontinental-type caldera in Newfoundland. Canadian Journal of Earth Sciences, Volume 24, number 6, pages 1135-1148. [NFLD/2295]
- Currie, K.L.
1976: Studies of granitoid rocks in the Canadian Appalachians, Part 2. *In* Report of Activities, Part A. Geological Survey of Canada, Paper 76-1A, pages 159-160.
- Dean, P.L.
1977: A report on the geology and metallogeny of the Notre Dame Bay area, to accompany metallogenic maps 12H/1, 8, 9 and 2E/3, 4, 5, 6, 7, 9, 10, 11 and 12. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-10, 20 pages. [NFLD/0979]
- 1978: The volcanic stratigraphy and metallogeny of Notre Dame Bay, Newfoundland. Memorial University of Newfoundland, Department of Geology, Report 7, 216 pages. [NFLD/0999]
- Dec, T., Swinden, H.S. and Dunning, G.R.
1997: Lithostratigraphy and geochemistry of the Cottrells Cove Group, Buchans–Roberts Arm volcanic belt: new constraints for the paleotectonic setting of the Notre Dame Subzone, Newfoundland Appalachians. Canadian Journal of Earth Sciences, Volume 34, pages 86-103.
- Dickson, W.L.
2000: Geology of the eastern portion of the Dawes Pond (NTS 12H/1) map area, central Newfoundland. *In*

- Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 2000-1, pages 127-145.
- 2001: Geology of the eastern portion of the Dawes Pond (NTS 12H/1) map area, central Newfoundland. Newfoundland and Labrador Department of Mines and Energy, Geological Survey, Map 2001-21 (1:50 000 scale), Open File 012H/01/1606.
- Dunning, G.R., Kean, B.F., Thurlow, J.G. and Swinden, H.S.
1987: Geochronology of the Buchans, Roberts Arm, and Victoria Lake groups and Mansfield Cove Complex, Newfoundland. *Canadian Journal of Earth Sciences*, Volume 24, pages 1175-1184.
- Dunning, G.R. and Krogh, T.E.
1991: Stratigraphic correlation of the Appalachian Ordovician using advanced U-Pb zircon geochronology techniques. Geological Survey of Canada, Paper 90-9, pages 85-92.
- Espenshade, G. H.
1937: Geology and mineral deposits of the Pilley's Island area. Newfoundland and Labrador Geological Survey, Bulletin No. 6, 60 pages. [GSNL 002E/12/0030]
- Evans, D.T.W.
1996: Metallogenic studies: Roberts Arm and Cutwell groups, Notre Dame Bay, Newfoundland. *In* Current Research. Newfoundland Department of Natural Resources, Geological Survey, Report 96-1, pages 131-148.
- Finney, S.C. and Ethington, R.L.
2000: Global Ordovician series boundaries and global event biohorizons, Monitor Range and Roberts Mountains, Nevada. Geological Society of America (2000) Annual Meeting, Reno, Nevada; Guidebook to Field Trip 15.
- Fordham, B.G.
1992: Chronometric calibration of mid-Ordovician to Tournaisian conodont zones: a compilation from recent graphic-correlation and isotope studies. *Geological Magazine*, Volume 129, pages 709-721.
- Fortey, R.A., Harper, D.A.T., Ingham, J.K., Owen, A.W. and Rushton, A.W.A.
1995: A revision of Ordovician series and stages from the historical type area. *Geological Magazine*, Volume 132, pages 15-30.
- Hayes, J.J.
1951: Preliminary map, Marks Lake, Newfoundland. Scale 1: 63 360. Geological Survey of Canada Paper 51-20. [GSNL 002E/05/0052]
- Helwig, J.A.
1969: Redefinition of the Exploits Group, Lower Paleozoic, northeast Newfoundland. *In* North Atlantic - Geology and Continental Drift. *Edited by* Marshall Kay. American Association of Petroleum Geologists, Memoir 12, pages 408-413. [GSNL 002E/0218]
- Horne, G.S. and Helwig, J.A.
1969: Ordovician stratigraphy of Notre Dame Bay, Newfoundland. *In* North Atlantic - Geology and Continental Drift. *Edited by* Marshall Kay. American Association of Petroleum Geologists, Memoir 12, pages 388-407. [GSNL 002E/0218]
- Huff, W.D., Davis, D., Bergstrom, S.M., Krekeler, M.P.S., Kolata, D.R. and Cingolani, C.
1997: A biostratigraphically well-constrained K-bentonite U-Pb zircon age of the lowermost Darriwilian Stage (Middle Ordovician) from the Argentine Pre-cordillera. *Episodes*, Volume 20, pages 29-33.
- Kean, B.F., Dean, P.L. and Strong, D.F.
1981: Regional geology of the Central Volcanic Belt of Newfoundland. *In* The Buchans Orebodies: Fifty Years of Geology and Mining. *Edited by* E.A. Swanson. Geological Association of Canada, Special Paper 22, pages 65-78. [NFLD/2232]
- Kerr, A.
1996: New perspectives on the stratigraphy, volcanology, and structure of island-arc volcanic rocks in the Ordovician Roberts Arm Group, Notre Dame Bay. *In* Current Research. Newfoundland Department of Natural Resources, Geological Survey, Report 96-1, pages 283-310.
- Landing, E., Bowring, S.A., Davidek, K.L., Rushton, A.W.A., Fortey, R.A. and Wimbeldon, W.A.P.
2000: Cambrian-Ordovician boundary age and duration of the lowest Ordovician Tremadoc Series based on U-Pb dates from Avalonian Wales. *Geological Magazine*, Volume 137, pages 485-494.
- Landing, E., Bowring, S.A., Fortey, R.A. and Davidek, K.
1997: U-Pb zircon date from Avalonian Cape Breton Island and geochronologic calibration of the Early Ordovician. *Canadian Journal of Earth Sciences*, Volume 34, pages 724-730.

- Loch, J.D.
2002: Trilobite biostratigraphy across the base of the Whiterockian series (Ordovician) for the proposed GSSP at Whiterock Canyon, Nevada. Geological Society of America (2002) Annual Meeting, Abstract with Program.
- MacLachlan, K.
1998: The Wild Bight Group, Newfoundland Appalachians: a composite Early to Middle Ordovician ensimatic arc and continental margin arc - arc rift basin. Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 210 pages.
- Maletz, J.
1997: Arenig biostratigraphy of the Pointe-de-Levy slice, Quebec Appalachians, Canada. *Canadian Journal of Earth Sciences*, Volume 34, pages 733-752.
- Maletz, J., Lofgren, A. and Bergstrom, S.M.
1995: The Diabasbrottet section at Mt. Hunneburg, Province of Vastergotland, Sweden; a proposed candidate for a global stratotype section and point (GSSP) for the base of the second series of the Ordovician System. *In Ordovician Odyssey; Short Papers for the 7th International Symposium on the Ordovician System. Edited by J.D. Cooper, M.L. Droser and S.C. Finney. Field Trip Guidebook - Pacific Section, Society of Economic Paleontologists and Mineralogists, Volume 77, pages 139-145.*
- McConnell, B.J., O'Brien, B.H. and Nowlan, G.S.
2002: Late Middle Ordovician olistostrome formation and magmatism along the Red Indian Line, the Laurentian arc - Gondwanan arc boundary, at Sops Head, Newfoundland. *Canadian Journal of Earth Sciences*, Volume 39, pages 1625-1633.
- Min, K., Renne, P.R. and Huff, W.D.
2001: Ar⁴⁰-Ar³⁹ dating of Ordovician K-bentonites in Laurentia and Baltoscandia. *Earth and Planetary Science Letters*, Volume 185, pages 121-134.
- Mitchell, C.E.
2001: New graptolite collections from the proposed Whiterock global stratotype section: Implications for correlation of the Narrows section and an alternative proposal for the location of the Middle Ordovician GSSP level. *In Ordovician Stratigraphy - an online discussion forum; <http://seis.natsci.csulb.edu/ordstrat/default.htm>*
- Mitchell, C.E., Chen, Xu, Bergstrom, S.M., Zhang, Y., Wang, Z., Webby, B.D. and Finney, S.C.
1997: Definition of a global boundary stratotype for the Darriwilian Stage of the Ordovician System. *Episodes*, Volume 20, pages 158-166.
- Nowlan, G.S.
1996: Geological Survey of Canada Paleontological Report 6-GSN-1996: Report on two samples from Lower Paleozoic strata of the Point Leamington area, northern Newfoundland; NTS 002E/06; CON # 1487.

1997: Geological Survey of Canada Paleontological Report 1-GSN-1997: Report on three samples from the Bay of Exploits area, north-central Newfoundland; NTS 2E/06; CON # 1501.
- Nowlan, G.S. and Thurlow, J.G.
1984: Middle Ordovician conodonts from the Buchans Group, central Newfoundland, and their significance for regional stratigraphy of the Central Volcanic Belt. *Canadian Journal of Earth Sciences*, Volume 21, pages 284-296. [NFLD/1564]

1987: Middle Ordovician conodonts from the Buchans Group. *In Buchans Geology, Newfoundland. Edited by R.V. Kirkham. Geological Survey of Canada, Paper 86-24, Economic Geology, Report 4.*
- O'Brien, B.H.
2001: Geology of part of the Robert's Arm map area (NTS 2E/5), western Notre Dame Bay. Scale 1:50 000. Newfoundland and Labrador Department of Mines and Energy, Geological Survey, Map 2001-38, Open File 002E/05/1160.
- O'Brien, B.H., Swinden, H.S., Dunning, G.R., Williams, S.H. and O'Brien, F.H.C.
1997: A peri-Gondwanan arc-back arc complex in Iapetus: early-mid Ordovician evolution of the Exploits Group, Newfoundland. *American Journal of Science*, Volume 297, pages 220-272.
- O'Brien, F.H.C. and Szybinski, Z.A.
1989: Conodont faunas from the Catchers Pond and Cutwell groups, central Newfoundland. *In Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 89-1, pages 121-125.*

- Okulitch, A.V.
2001: Geological time scale, 2001. Geological Survey of Canada, Open File 3040 (National Earth Science Series, Geological Atlas).
- Pope, A.J., Calon, T.J. and Swinden, H.S.
1990: Stratigraphy, structural geology and mineralization in the Gullbridge area, central Newfoundland. *In* Metallogenic Framework for Base and Precious Metal Deposits, Central and Western Newfoundland [Field Trip 1]. *Edited by* H.S. Swinden, D.T.W. Evans and B.F. Kean. Field Trip Guidebook for 8th IAGOD symposium, Geological Survey of Canada, Open File 2156, pages 93-105.
- Pudifin, M.
1993: Roberts Arm volcanics in the Gullbridge Mine area: deep exploration for Kuroko-type massive sulphides. *In* Ore Horizons, Volume 2. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Branch, pages 77-88.
- Swinden, H.S.
1987: Geology and mineral occurrences in the central and northern parts of the Roberts Arm Group, central Newfoundland. *In* Current Research, Part A. Geological Survey of Canada Paper 87-1A, pages 381-390.
- Swinden, H.S. and Sacks, P.E.
1996: Geology of the Roberts Arm belt between Halls Bay and Lake Bond, Newfoundland (parts of NTS 12H/1 and 8). Newfoundland Department of Mines and Energy, Geological Survey, Map 96-32 (1:50 000 scale), Open File 012H/1367.
- Thirlwall, M.F. and Fitton, J.G.
1983: Sm-Nd garnet age for the Ordovician Borrowdale Volcanic Group, English Lake District. *Journal of the Geological Society of London*, Volume 140, pages 511-518.
- Thurlow, J.
1996: Geology of a newly discovered cluster of blind massive-sulphide deposits, Pilley's Island, central Newfoundland. *In* Current Research. Newfoundland Department of Natural Resources, Geological Survey, Report 96-1, pages 181-189.
- Thurlow, J.G. and Swanson, E.A.
1987: Stratigraphy and structure of the Buchans Group. *In* Buchans Geology, Newfoundland. *Edited by* R.V. Kirkham. Geological Survey of Canada, Paper 86-24, Economic Geology Report 2, pages 35-46.
- Tucker, R.D. and McKerrow, W.S.
1995: Early Paleozoic chronology: a review in light of a new U-Pb zircon ages from Newfoundland and Britain. *Canadian Journal of Earth Sciences*, Volume 32, pages 368-379.
- Whalen, J.B. and Currie, K.L.
1988: Geology, Topsails Igneous Terrane, Newfoundland. Geological Survey of Canada, Map 1680A; Newfoundland Department of Mines and Energy Geofile. [GS#NFLD/1898]
- Whalen, J.B., Jenner, G.A., Longstaffe, F.J., Robert, F. and Gariépy, C.
1996: Geochemical and isotopic (O, Nd, Pb and Sr) constraints on A-type granite petrogenesis based on the Topsails Igneous Suite, Newfoundland Appalachians. *Journal of Petrology*, Volume 37, pages 1463-1489.
- Williams, H.
1962: Geology, Botwood (west half), Newfoundland. Geological Survey of Canada, Preliminary Map 19-1962. [GSNL 002E/0109]
1963: Botwood map area. *In* Summary of Research: Field, 1962. Geological Survey of Canada, Paper 63-01, page 60. [NFLD/2035]
- Williams, H., Colman-Sadd, S.P. and Swinden, H.S.
1988: Tectonic-stratigraphic subdivisions of central Newfoundland. *In* Current Research, Part B. Eastern and Atlantic Canada. Geological Survey of Canada, Paper 88-01B, pages 91-98. [NFLD/2022]
- Williams, S.H., Barnes, C.R., O'Brien, F.H.C. and Boyce, W.D.
1994: A proposed global stratotype for the second series of the Ordovician System: Cow Head Peninsula, western Newfoundland. *Bulletin of Canadian Petroleum Geology*, Volume 42, pages 219-231.
- Williams, S.H. and Tallman, P.
1995: Graptolite-based evidence for a revised stratigraphic and structural setting of the Szechuan, Hunan and Xingchang antimony prospects, Exploits Subzone, central Newfoundland. *Atlantic Geology*, Volume 31, pages 89-93. [002D/11/0303]