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STRATIGRAPHY AND STRUCTURE OF THE TOMMY'S ARM RIVER–SHOAL ARM BROOK AREA (NTS 2E/5) WITH REFERENCE TO THE STRATABOUND ALTERATION ZONES OF THE UPPER WILD BIGHT GROUP, NORTH–CENTRAL NEWFOUNDLAND

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ABSTRACT

Most of the Tommy's Arm River–Shoal Arm Brook area is underlain by low-grade sedimentary rocks of Middle and Late Ordovician age, that belong to the Wild Bight Group and Gull Island Formation of the Exploits Subzone. However, in the extreme northwest and southwest map area, sedimentary and volcanic rocks are assigned to the Middle Ordovician or younger Sops Head Complex and Early or mid-Ordovician Roberts Arm Group (Notre Dame Subzone). All of these map units are intruded, post-tectonically, by the Siluro-Devonian plutons of the Twin Lakes Diorite Complex.

Late Ordovician or younger juxtapositioning of the Exploits and Notre Dame subzones initially resulted in the tectonic emplacement of the thrust-bounded Wild Bight Group above the Sops Head Complex and the Roberts Arm Group. Subsequently, the Wild Bight Group was structurally overidden by the Sops Head Complex and Roberts Arm Group, and was internally fault-imbricated.

Highly altered and replaced turbidites in the upper Wild Bight Group have potential for SEDEX-type mineralization, especially near gabbro laccoliths. Base-metal prospects are located in Roberts Arm tholeiites, structurally isolated from the rest of the Crescent Lake Formation. The known gold occurrences are associated with ductile faults in the Sops Head Complex.

INTRODUCTION

PREVIOUS WORK

The earliest regional geological maps of the Roberts Arm (NTS 2E/5) map area were produced in the 1930s for Newfoundland's Commission of Government during the Princeton University Expeditions. They covered the northwestern part of the map area and focussed on the well exposed and inhabitated coastal region. Espenshade (1937) established sedimentary and volcanic rock units such as the Gull Island, Shoal Arm and Beaver Bight formations and the older Wild Bight Volcanics along the coast between Bird Island Cove, on the northwest shore of Badger Bay, and Wild Bight, at the bottom of this bay (Figure 1). His work demonstrated the lithological continuity and tectonic linkage of the Badger Bay area with the Bay of Exploits–New Bay region to the east (Heyl, 1936). In essence, Espenshade (*op. cit.*) defined what would later become accepted as the Ordovician stratigraphic template of the Exploits Subzone of the Dunnage Zone (Williams *et al.*, 1988).

With Newfoundland joining the Canadian Confederation, J.J. Hayes of the Geological Survey of Canada carried out the first systematic mapping of the western half of the Roberts Arm map area (Hayes, 1951). Both he and Espenshade considered the ground between Bird Island Cove and Tommy's Arm, east of Crescent Lake (Figure 1), to be pivotal in regional stratigraphic and structural interpretations. In the opinion of most subsequent workers, however, Hayes (1951) and Esphenshade (1937) incorrectly grouped their Roberts Arm Volcanics and Crescent Lake Formation in the Exploits Group (or other Exploits Subzone equivalents) rather than placing them within the Notre Dame Subzone (Williams *et al.*, 1988) of the Dunnage Zone (*see* van der Voo *et al.*, 1991 for an alternative hypothesis). Furthermore, they considered their Burtons Head (Figure 1) and parts of their Julies Harbour map units (the tracts southeasterly adjacent to the

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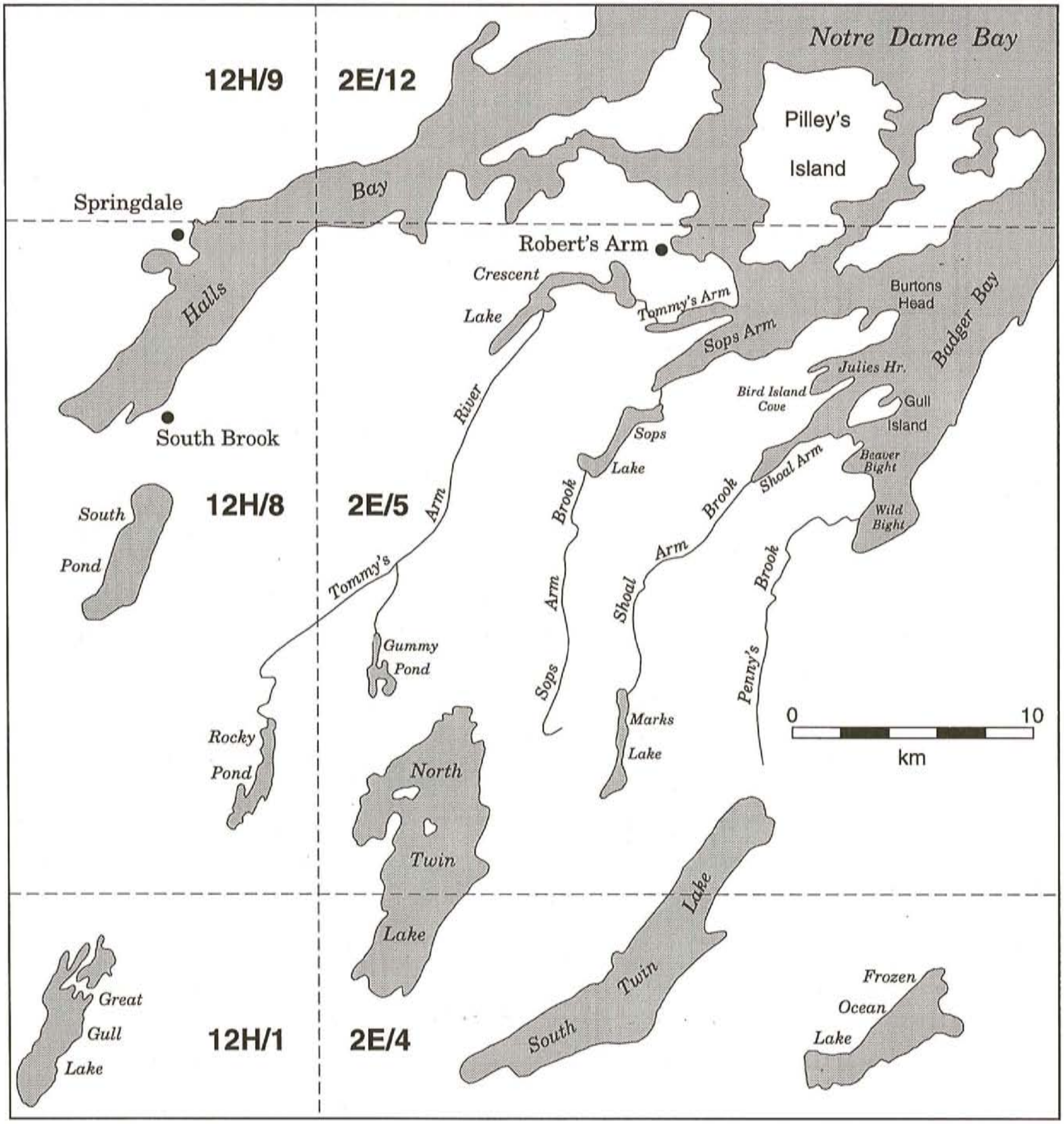

Figure 1. *Geographic location of the Tommy's Arm River–Shoal Arm Brook area of western Notre Dame Bay. Boundaries of the Roberts Arm [NTS 2E/5] map sheet are indicated.*

Crescent Lake Formation) to have been stratigraphically continuous with the Gull Island–Shoal Arm–Beaver Bight–Wild Bight sequence. In the coastal section, neither Hayes nor Esphenshade identified a structural feature of the rank of the Red Indian Line (i.e., the Exploits Subzone–Notre Dame Subzone boundary or the Gondwana–Laurentia suture within the Dunnage Zone; Colman-Sadd *et al.*, 1992).

Ironically, Hayes (1951) originally recognized several fundamental structural features (O'Brien, 1991; O'Brien *et al.*, 1994) of Exploits Subzone rocks that lie adjacent to the Red Indian Line elsewhere in the Dunnage Zone. First, he mapped out a complexly refolded domal structure, north of North Twin Lake (Figure 1), within what is now considered to be the upper part of the Wild Bight Group. The interference pattern was outlined by his Beaver Bight member, a map unit that encircled his underlying Wild Bight Formation. (The Beaver Bight member of Hayes (1951) replaced Espenshade's (1937) Beaver Bight Formation but both were subsequently included in Dean's (1977) Pennys Brook Formation – *see* Figure 1 for place names). Second, to the west of North Twin Lake, highly deformed sedimentary strata were correlated with the Burtons Head–Julies Harbour sequence, and were assigned to an Ordovician unit now known to contain meange and formations from both the Exploits and Notre Dame subzones. Hayes' (1951) observations on the disposition of rock units in the westernmost part of the NTS 2E/5 map area are consistent with the repetition of the units by regional fault imbrication and large-scale polyphase folding, phenomena seen throughout Notre Dame Bay near the Red Indian Line structural zone.

In 1963, H. Williams produced a 1:253 440-scale geoogical map of the NTS 2E district as part of a regional synthesis of the Notre Dame Bay area (*see* Williams, 1962, 1972). He assigned all of Hayes' (1951) map units between Tommy's Arm and Beaver Bight (Figure 1) to the Exploits Group, utilizing Helwig's (1969) as opposed to Heyl's (1936) definition. In this way, the Middle and Upper Ordovician strata contained in the Shoal Arm–Gull Island succession were positioned stratigraphically above the Middle Ordovician and older Wild Bight Formation, which Williams (1963) elevated to group status. At this time, he also placed the Crescent Lake Formation and the Roberts Arm Volcanics in the Roberts Arm Group, and considered the mutual boundary of the redefined Exploits and Roberts Arm groups to be, everywhere, a faulted contact.

Dean (1977) included the entire Roberts Arm (NTS 2E/5) map area in a series of metallogenic maps of north-central Newfoundland; in these publications, he consistently compiled the regional geology at 1:50 000 scale for the first time. Dean (*op. cit.*) separated the Wild Bight Group into five conformable formations and originally proposed an internal stratigraphy for what he considered were its Lower and Middle Ordovician rocks. In the area surveyed, various types of Wild Bight volcaniclastic strata were all placed within his uppermost division, the Pennys Brook Formation.

Several fossil-bearing units of Middle to Late Ordovician age in the Badger Bay–North Twin Lake region of the Exploits Subzone were revised following Dean's compilation work. He amended the Shoal Arm Formation by adjusting its upper and lower boundaries; the name Gull Island Formation was informally dropped. To avoid direct correlation with Helwig's (1969) Point Leamington Greywacke, Dean (1977) used the name Sansom Greywacke to refer to partly equivalent strata in the Badger Bay area, as he thought the latter to be the more generic term. In 1991, S.H. Williams formally erected the Point Leamington Formation and proposed that this unit should supersede the Sansom Formation. Williams *et al.* (1995) subsequently addressed this problem of regionally applicable stratigraphic nomenclature by introducing the term Badger Group to include all mid-Late Ordovician and early Silurian greywacke and conglomerate formations in the Exploits Subzone.

Dean (1977) thought that a continuous Pennys Brook–Shoal Arm–Sansom stratigraphic sequence was repeated about a doubly plunging major anticline in the western part of the Roberts Arm map area. He interpreted the dome in the Exploits Subzone near North Twin Lake (Hayes, 1951) to have formed as a result of plunge culmination.

The stratigraphic and structural setting of rocks in the northwestern part of the Roberts Arm map area, which are now included within Early and Middle Ordovician sequences of the Notre Dame Subzone, were illustrated in regional cross sections constructed by Dean (1977). He stated that the sedimentary rocks of the Crescent Lake Formation were stratigraphically overlain by the mafic volcanic rocks found in the southeasternmost tracts of the Roberts Arm Group. Moreover, he interpreted Crescent Lake chert and wacke as most commonly occurring in fault-bounded anticlines structurally emplaced through a younger veneer of Roberts Arm basalt.

Within the Red Indian Line structural zone of this paper, Dean (1977) erected new rock units. The Burtons Head–Julies Harbour sequence, which was previously assigned group, formation or member status, was formally abandoned. Instead, Dean (*op. cit.*) introduced the term Sops Head Complex, included this melange-bearing lithostratigraphic unit in the Roberts Arm Group, and positioned it immediately beneath the Crescent Lake Formation.

In his 1981 paper, K.D. Nelson correlated the Sops Head Complex with the Boones Point Complex of the Fortune Harbour Peninsula to the east and concurred with Dean (1977) in placing the melange unit structurally below a northwest-dipping succession of the Roberts Arm Group. However, he thought that the mid-Ordovician blocks in the melange were derived from the Roberts Arm Group, which was overthrust from the northwest toward the southeasterly adjacent strata of the Exploits Subzone. Moreover, Nelson (1981) portrayed the mainly unbroken volcanosedimentary formations of the Sops Head Complex, which are situated between the melange tract and his Late Ordovician Gull Island Formation, to have belonged to the Wild Bight Group and not the Roberts Arm Group.

The regional relationships of informal map units of volcanic and volcaniclastic rocks were depicted in Swinden's (1987) geological map of the Wild Bight Group. Although only the eastern half of the Roberts Arm map area was surveyed, he considered the type area of the Pennys Brook Formation (Penny's Brook, Figure 1) to be a region where the pillow lavas and mafic breccias of the Badger Bay volcanic unit were stratigraphically intertongued with Pennys Brook volcaniclastic sedimentary rocks. Both units were shown to underlie Espenshade's Beaver Bight Formation (i.e., an abandoned unit at the base of or immediately below the Shoal Arm Formation). Swinden (1987) determined that his Badger Bay volcanic unit of the upper Wild Bight Group contained alkalic and MORB-like basalts and interpreted them as having erupted in a back-arc basin. In contrast, older Wild Bight Group rocks farther east were interpreted to have originated in a volcanic island arc.

In 1988, H.H. Bostock of the Geological Survey of Canada released a detailed 1:50 000-scale geological map of the northern part of the Roberts Arm Group and adjacent lithostratigraphic units. He confirmed that the Wild Bight Group, Shoal Arm Formation and Sansom Formation locally comprised the Exploits Subzone, and that this conformable succession was everywhere in tectonic contact with Notre Dame Subzone rocks. Within the NTS 2E/5 map area, Bostock (1988) affirmed that the Notre Dame Subzone was solely represented by the Roberts Arm Group. Furthermore, he stated that this dominantly calc-alkaline volcanic group consisted of several fault-bounded "terranes", each of which have a conformable internal stratigraphy (*see* Kerr, 1996). Accepting the position of previous workers, Bostock (*op. cit.*) considered the sedimentary rocks of the Crescent Lake Formation to have had stratigraphically underlain the tholeiitic volcanic rocks of his Crescent Hump and Southwest Crescent "sub-terranes".

The Sops Head Complex of the Red Indian Line structural zone was postulated to be Late Ordovician or Early Silurian (cf. Nelson, 1981) and to be in tectonic contact with a variety of lithostratigraphic units from both subzones (Bostock, 1988). The Early Silurian terrestrial strata of the Springdale Group were inferred to have unconformably overlain the complexly deformed marine strata of the Sops Head Complex.

LOCATION AND ACCESS

The area surveyed is bounded to the south by North Twin Lake, to the west by Tommy's Arm River, to the north by Sops Lake, and to the east by Shoal Arm Brook (Figure 1). Most of this 185 km^2 region can be reached by forestry access roads and allied tracks. Rocks in the southern part of the area are accessible by boat.

'LOCAL' AGE OF STRATIFIED ROCK UNITS

Within the map area, Wild Bight Group strata have not been biostratigraphically or absolutely dated. However, the presence of alkali pillowed basalts between Shoal Arm Brook and Pennys Brook (Swinden, 1987) may imply an early Llanvirn or younger age (*cf.* O'Brien *et al., in press*) for these beds and strata farther west, early Arenig or older Wild Bight rocks are known to occur east of the map area (G. Dunning, unpublished data, 1992).

During regional mapping for this project, abundant graptolites were found in the black shales of the overlying Shoal Arm Formation, although none have been identified and assigned to Newfoundland graptolite biozones. However, Clarke (1992) has reported forms typical of the upper Caradoc *Dicranograptus clingani* Zone from the Shoal Arm Formation southwest of Sops Lake.

The base of the Gull Island Formation, particularly the section exposed in the hinge zone of the major anticline in the northeast part of the map area, is notably fossiliferous. However, at present, these graptolites remain unspeciated. Conglomerate lenticules, locally well developed in sandstone turbidites of the lower Gull Island Formation, contain limestone clasts yielding a Llandeilo conodont fauna in areas adjacent to the Red Indian Line structural zone (Clarke, 1992).

Fossils from the Sops Head Complex, collected by various workers over the past two decades, constrain the maximum depositional age of this unit and provide an older limit on the age of regional deformation along this part of the Red Indian Line (Nelson, 1981; Bostock, 1988; Clarke, 1992). This data comes from conodont-bearing Llanvirn–Llandeilo limestones that form either blocks in melange units or are interbedded with volcanic flows in unbroken volcaniclastic successions. Age information is also gleaned from graptolite-bearing Caradoc shale, which separates undated pyritic mudstone–pebble microconglomerate–sandstone turbidite sequences included within the Sops Head Complex.

In the map area, the Roberts Arm Group has not been directly dated. Bostock (1988) stated that some fossil-bearing blocks in the Sops Head Complex were derived from the Roberts Arm Group, and that this relationship probably indicated that parts of the group were mid-Ordovician in age (e.g., the sedimentary and volcanic rocks of the southeastern Crescent Lake Formation; *see* Clarke (1992) for alternative interpretation). One of the fault-bounded tracts of calc-alkaline volcanic rocks located farther northwest in the Roberts Arm Group (Boot Harbour terrane of Kerr, 1996) has been isotopically dated as early Ordovician (late Arenig; Dunning *et al.*, 1987).

LITHOSTRATIGRAPHY

Stratified rock units from the Exploits Subzone, the Red Indian Line structural zone and the Notre Dame Subzone are herein described in the context of either the local depositional succession or the tectonic rock sequence. In addition, pre-tectonic gabbro laccoliths are briefly discussed in the section on the lithostratigraphy of the Exploits Subzone.

EXPLOITS SUBZONE

The Ordovician rocks of the Wild Bight Group, Shoal Arm Formation and Badger Group locally represent the stratified units of the Exploits Subzone. Northwest of Shoal Arm Brook, the Badger Group is seen to be in gradational contact with the underlying Shoal Arm Formation (Figure 2). In this same area, and also southwest of Sops Lake, the Wild Bight Group is observed to conformably underlie the Shoal Arm Formation (Figure 2).

Wild Bight Group

In the map area, the Middle Ordovician and older Wild Bight Group is mostly composed of sandy and argillaceous epiclastic turbidites, which have been previously assigned to the Pennys Brook Formation. The minimum stratigraphic thickness of this formation is approximately 2 km in the area surveyed.

Between Tommy's Arm River and Shoal Arm Brook, the Pennys Brook Formation is a cyclothemic fining-upward succession. For the most part, it consists of a monotonous alternating sequence of green banded argillite and grey volcaniclastic wacke. Siliceous argillites are commonly mottled and generally thin-bedded. Wackes vary from conglomeratic to sandy in grain size and are thin and thick bedded. Decimetric-scale graded beds contain wacke above their lower contact and banded argillite below the upper surface of the bed.

Volcaniclastic Strata of the Pennys Brook Formation

Pebbly and tuffaceous wacke containing mixed mafic and felsic volcanic clasts form a significant proportion of the Pennys Brook Formation. Basalt fragments illustrate wide textural variations and represent the ubiquitous lithic component of these volcaniclastic rocks. Large, well-rounded, mafic volcanic clasts indicate that near-source erosion preceeded transport and accumulation within the upper Wild Bight basin.

In contrast, the less common fragments of felsic volcanic rocks are restricted to certain horizons in the Pennys Brook Formation. Felsic fragments are porphyritic, flow-layered and glassy. Locally, delicate fiamme and pumice exhibiting feathered edges are preserved. This suggests that such deposits may be waterfall tuffs exploded from a contemporaneous volcanic centre. Alternatively, they may represent airfall tuffs in which the felsic tephra underwent limited reworking and submarine transport.

In places, debrite horizons having sharp basal contacts are interstratified with typical Pennys Brook argillite and wacke. Such debrites contain large well-bedded sedimentary rafts that are lithologically similar to strata in underlying and overlying argillite–wacke cyclothems. Partially detached slump folds, in which the buckled layers of graded wacke and banded argillite are either interbedded or admixed, are completely enclosed by the debrite matrix. Angular rip-up clasts of siliceous argillite are also present in the unsilicified matrix of these debrites.

In the area between Sops Arm and Shoal Arm brooks, reworked volcanic breccia and agglomerate are locally present in the upper part of the Pennys Brook Formation (Figure 2). There, they comprise mappable lenticles of variable thickness and strike length. In well-exposed localities, these pyroclastic rocks are demonstrably laterally discontinuous. Developed at several stratigraphic intervals within the argillite–wacke succession, the lenticles are larger, thicker and more numerous toward the east.

Poorly sorted sedimentary rocks and graded breccias having outsized sedimentary and volcanic blocks are included in the thick mafic tuff-dominated lenticles. The coarser grained breccias contain conspicuous basalt porphyry fragments that have not been recognized in the western part of the Pennys Brook Formation. Near the base of some lenticles, polylithic agglomerates are associated with chaotically slumped debris-flow deposits. Where diabase dykes intrude such debrites, they display straight chilled margins that traverse several of the randomly oriented blocks as well as the surrounding matrix.

Sedimentology

In the Pennys Brook Formation, it appears that the low-energy background sediment is an argillite in which cross-laminated silt was deposited above fine parallel-laminated sand. In some beds, both were originally capped by a minute interval of structureless mud. The background sediments were scoured and overlain by high-energy deposits. These are generally thicker, much coarser and less sorted than the argillaceous strata. Such sediments are represented by the Pennys Brook wackes, which contain intrabasinal sedimentary clasts mixed with abundant extrabasinal volcanic clasts.

The majority of sedimentary rocks in the Pennys Brook Formation show evidence of deposition from gravity-driven mass flows such as turbidity currents, fluidized flows, or debris flows. Deposits interpreted to have formed from turbidity currents are preferentially located in the well-bedded

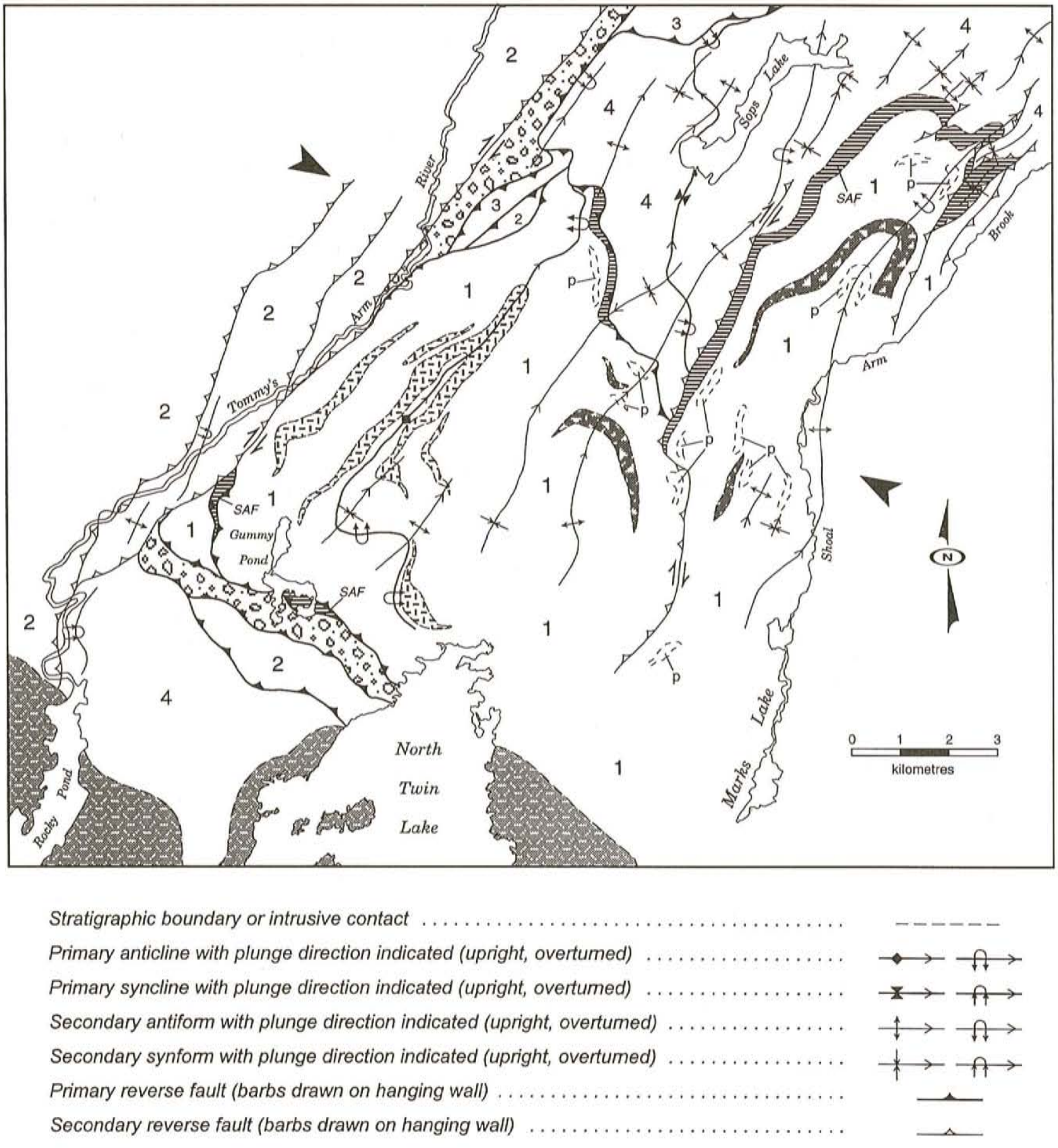

Figure 2. *Geological map of the Tommy's Arm River–Shoal Arm Brook area illustrating some of the major structures. Numbered units are (1) the Wild Bight Group, (2) the Crescent Lake Formation of the Roberts Arm Group, (3) the unbroken formations of the Sops Head Complex, and (4) the Badger Group. Patterned units include the melange tracts of the Sops Head Complex ( ), the Shoal Arm Formation ( ), and the Twin Lakes diorite ( ). Also depicted by patterns are mafic agglomerate–debrite units ( ), pseudoporphyroblast-bearing alteration zones (p), and gabbro sills ( ), all found in the upper Wild Bight Group.* Modified from *O'Brien and MacDonald (1996). Arrows indicate approximate line of composite section shown in Figure 3. SAF = Shoal Arm Formation.*

parts of the formation. Ascending the local Pennys Brook sequence, there appears to be a systematic variation in the type of Bouma intervals represented. Differences are also seen in the degree of basal scouring at the base of a turbidite, in the formation and preservation of grading in the Bouma A division, and in the extent to which ripple lamination and other traction-controlled structures developed in the Bouma C division.

Deposits interpreted to have formed from fluidized flows show large variations in the degree of sediment amalgamation within beds and in the extent of sandstone dyking. They are common in argillite–sandstone multilayers, which exhibit large ductility and permeability contrasts. In the Pennys Brook Formation, these features are directly related to the amount of loading-related and compaction-generated structures observed in particular sections. This presumably implies that liquefaction was operative at different times in certain parts of the depositional basin.

Debrites and other mixtites interpreted to have formed by debris flows constitute a comparatively small part of the total thickness of the Pennys Brook Formation. Typically, they form where unstratified horizons of very coarse agglomerate rest directly above, or are localized between, very thin-bedded argillite sequences. Presumably the combination of strong matrix cohesion in the argillite and high porosity in the agglomerate favours debris-flow formation.

Gummy Brook Gabbro

The most abundant and largest of the pretectonic intrusive suites in the map area are herein referred to as the Gummy Brook gabbro (Figure 2). Most of these intrusions are sills composed of medium-grained equigranular gabbro; however, minor dark-grey diorite sheets are also present. In certain places, coarse-grained glomerocrystic gabbros are intruded by multiple (one-sided) diabase dykes. Gabbro sills, up to 75 m thick and 4.5 km long, are most common in the lowest observed part of the Pennys Brook Formation (Figure 2).

Although there are numerous exposures of the chilled vesicular margins of these shallow-level intrusions, spotted hornfelses of contact metamorphic origin have not been observed in adjacent sedimentary rocks. Some of the smaller bodies possibly display an upper pepperititic margin where they intrude contorted tuffaceous laminites. The regionally folded laccoliths of Gummy Brook gabbro are possibly correlative with the early Llandeilo Thwart Island gabbros of the Exploits Group to the east (O'Brien *et al.*, *in press*).

Diagenesis and Alteration

In the area surveyed, most strata in the Wild Bight Group contain nodules or concretions and are variably silicified. In places, where the regional metamorphic grade is low and intrusions are absent at the surface, spectacular zones of pretectonic pseudoporphyroblasts are present in the upper part of the Pennys Brook Formation (Figure 2).

Stratabound alteration zones are extensively developed within turbidite sequences that are also characterized by diagenetic replacement textures such as chert orbicules or mineralogically zoned concretions. In the Shoal Arm Brook area, several discrete alteration zones are separated by the lenticles of volcanic breccia and debrite in the Pennys Brook Formation. A close spatial relationship exists between nodular turbidite sequences, chertified iron-rich argillite horizons and pseudoporhyroblast-bearing alteration zones. This association is confined to the Wild Bight Group, although nodular Mn-rich coticules are present in the Shoal Arm Formation below the gold-bearing black shale division (Dean and Meyer, 1983; Sangster, 1992).

The largest and greatest number of Gummy Brook sills are emplaced at stratigraphic levels well below the pseudoporhyroblast-bearing alteration zones and the mafic tuff–debrite lenticles (Figure 2). Although a few gabbro–diorite intrusions are present in the upper part of the Pennys Brook Formation, none have been observed in the Shoal Arm Formation.

Alteration Zone Mineralogy

The stratabound alteration zones in the Wild Bight Group are characterized by silicate, carbonate and sulphide assemblages that are either coarsely spotted or finely disseminated. Calc-silicate pods are locally present. Silicate pseudoporphroblasts include skeletal garnet, Fe-rich biotite and an unusually birefringent mineral of the mica group. Actinolite, epidote, chlorite, zoisite, tourmaline and quartz occur as matrix disseminations. Some of the mineral species in the matrix are also found as pseudomorphs replacing biotite and garnet. The presence of coexisting garnet, biotite and chlorite possibly indicates that the temperatures of fluids operative in the alteration zones were considerably hotter than the temperatures produced during peak regional metamorphism (a conodont alteration index of 4.5 has been reported by Clarke (1992) from the Red Indian Line structural zone).

Carbonates of probable ankerititic or sideritic composition occur in veinlets and as spotted aggregates where original grey-green turbidites are completely altered to brown. However, in most parts of the alteration zones, these Fe–Mn-rich carbonates are seen to be disseminated throughout the rock matrix. Generally, the turbidites were thoroughly silicified and then affected by the carbonate alteration. The only opaque mineral to be identified to date is pyrite, though pyrrhotite, magnetite, hematite, illmenite and tellurides are common near mineralized sediment-sill complexes elsewhere (e.g., Ray *et al.*, 1996). Some of the vertical magnetic gradient anomalies (Anonymous, 1988) in the altered turbidites of the Pennys Brook Formation should be investigated with magnetic sulphide- or magnetic oxide-generating reactions in mind.

Diagenetic Replacement Textures

In the map area, zoned concretions typically display concentric rings, each one composed of different minerals. In some localities, concentric zonation is produced by textural variants of the same mineral species. Such minerals are not necessarily present in the host rock. In contrast, nodules possess a carbonate nucleus or have a core of secondary quartz aggregates. They are also outlined by variably diffuse spheres of leached host rock. In such nodules, each lithic band illustrates a different degree of hardness.

Certain turbidites in the Pennys Brook Formation were strongly mottled during diagenesis but still preserve relict Bouma divisions. Concretions are so abundant in these mottled strata that they come to touch and crowd each other. As they interface, the concretions displace and overgrow one another, some at different stages of mineralogical growth than others. In some exceptional exposures, concretions have been linked together, laterally and vertically, to form three-dimensional vermicular networks. Extending from the bottom to the top of individual beds, this type of mottling is fundamentally distinct from the bioturbation-related mottling seen in the black shale–grey chert intervals of the upper Shoal Arm Formation.

Concretions and nodules vary from spheroidal to ellipsoidal in shape. In some places, oblate discoidal and perfectly round forms are present in adjacent beds, especially where large competancy contrasts exist across sharp bedding planes. Siliceous nodules, zoned from light grey to white, were preferentially nucleated along the upper surfaces of ungraded sandstone and siltstone beds. They are best developed where the overlying bed is a relatively impermeable laminated argillite. The central cores of some nodules are composed of netveined pieces of chloritized argillite. This suggests that they had nucleated in turbidites that had already begun to be altered.

Spotted assemblages of epidote group minerals predominate in argillaceous interbeds in some of the turbidite-hosted alteration zones. Epidote aggregates, which have a minute granular core composed of relict feldspars, are reversely graded in places. In dark-green beds, these spots develop large aspect ratios as a consequence of them being flattened within highly compacted layers. The epidotes define a strong bedding-parallel foliation, which has augened and reorientated nodules inside selected turbidite laminae. In the most compacted stratigraphic layers, platey epidote grains wrap extremely oblate nodules that had developed asymmetric tails as a result of rigid body rotation during shear along subhorizontal bedding planes.

Synsedimentary Replacement and Alteration

Vertical crack-seal veinlets having horizontal fibres are confined to nodules and concretions that are compacted in the plane of bedding. They taper upward and downward, dying out toward the external boundaries of these ellipsoids. In places, veinlets crosscut relict bedding lamination within nodules. Some intra-veinlet fibres developed concomitantly with the mineralogical zonation of ellipsoidal concretions. They indicate that, during diagenesis and burial, the lithostatic load produced regularly spaced vertical fractures in relatively stiff, well-layered beds. The fibre direction inside veinlets indicates that silicified concretionary beds (nodular hardgrounds) were horizontally stretched and pulled apart at the same time the beds were still being compacted. Though stiff during dilation, some competent boudinaged layers became buckled as adjacent incompetent layers were slump folded.

In some sections, banded nodular argillites are interbedded with wackes that are inferred to have had a high porosity prior to consolidation. Here, silicified argillite boudins were drag folded near the margins of sandstone dykes as the wackes underwent liquefaction during loading. It seems that these synsedimentary dykes utilized the boudin neck as a breakthrough point to inject fluidized sand and pebbles upward into the overlying sequence. Rectangular cobbles and boulders of siliceous banded argillite are a conspicuous clastic component of some wackes in the Pennys Brook Formation. The regular geometry and advanced induration of these outsized intraclasts suggest that they may have been jointed and silicified prior to being incorporated into the wacke deposits.

The diagenetic replacement of turbidite beds is texturally related to the nucleation of stratabound pseudoporphyroblasts. In some alteration zones hosted by the Pennys Brook Formation, siliceous argillite beds display turquoise concretions that have outer rings in which Fe-rich chlorite and celadonite pseudoporphyroblasts are spectacularly developed. A younger age limit on at least one stage of this replacement and alteration is provided by overlying sedimentary rocks in the same formation. In the northeastern part of the map area, spotted concretions are found as detrital clasts, along with transported polylithic blocks, in a wacke–debrite sequence. There, the resedimented concretions are observed to be either completely detached or partly enclosed in the original host rock. In one locality, a reworked fragment of porphyritic diorite sits in a concretion-bearing debris-flow deposit, implying either sub-seafloor diorite intrusion or deep scouring and faulting accompanying sediment flow.

Shoal Arm Formation

In ascending stratigraphic order, the Shoal Arm Formation generally consists of i) thin interbeds of green siliceous crosslaminated argillite and turquoise chert, ii) red nodular chert and coticule-bearing laminites, iii) manganiferous siltstone and grey chert, and iv) black graptolitic shale. The formation is thought to range from the mid to late Ordovician, although total stratigraphic thickness is approximately 150 m and the black shale division is less than 50 m thick.

The Shoal Arm Formation is similar, though lithologically and biostratigraphically distinct, from the Llandeilo–Caradoc Lawrence Harbour Formation to the east (Williams and O'Brien, 1994). Both formations are excluded from, but rest conformably below, the sedimentary strata of the Badger Group. In the map area, the section of transitional beds between Shoal Arm and Gull Island formations is some 20 m thick.

In several places, discontinuous sections of highly disrupted black shales from the Shoal Arm Formation lie tectonically adjacent to the Sops Head Complex (Figure 2). There, they locally separate the block-in-matrix melange tracts from the Wild Bight Group.

Badger Group

The Late Ordovician Gull Island Formation of the Badger Group is mainly made up of sandstone turbidites interbedded, in its lower part, with dark-grey siltstone. Total stratigraphic thickness is estimated to be in excess of 1 km in the area surveyed.

Most turbidites in the Gull Island Formation occur in alternating thin- and thick-bedded sequences of light-grey sandstone. Excellent examples of complete Bouma cycles are preserved in Gull Island turbidites, although quicksands commonly illustrate evidence of bed loading and allied thixatropic deformation. Such siliciclastic strata are quite distinct from the green epiclastic and calcareous turbidites of sandstone-bearing map units in the Roberts Arm and Wild Bight groups. Volcanic flows have not been recognized at any stratigraphic level of the Gull Island Formation.

Minor dark-grey siltstone interbeds are located in the lower part of the Gull Island Formation well above the transitional beds at the base of this unit. They are reminiscent of the stratigraphic interval between the *Dicellograptus complanatus* and *Dicellograptus anceps* graptolite biozones in the Ashgill Point Leamington Formation (Williams *et al.*, 1992), though the Gull Island beds are less shaley and the sequence is considerably thinner.

In the map area, the Gull Island Formation is devoid of the regionally mappable lenticles of polymictic conglomerate that typify some of the other Badger Group formations in Notre Dame Bay. Rare beds of pebbly wacke and cobble conglomerate are, however, situated east of Sops Lake. A discontinous fossil-bearing horizon, some 50 m in thickness and 750 m in strike length, is localized along the western flank of the Badger Group synclinorium.

RED INDIAN LINE

Most sequences of stratified rocks in the Sops Head Complex cannot be readily assigned to particular intervals of any of the established regional lithostratigraphic units of the northern Dunnage Zone. For this reason, these mainly unbroken formations have a unique map unit designation (Figure 2).

Some of the complex's variably deformed stratified sequences are known or assumed to be the biostratigraphic equivalents of certain groups or formations that crop out adjacent to the Red Indian Line. However, the unbroken formations of the Sops Head Complex are unique by comparison and possess distinctive lithofacies associations, petrochemistry and internal stratigraphy (Bostock, 1988; Clarke, 1992).

Unbroken Formations of the Sops Head Complex

In negligibly deformed parts of the complex, green epiclastic turbidites and interbedded tuffaceous sandstone display primary sedimentary structures and abundant geopetal indicators. They are observed to comprise continuous stratigraphic successions as great as 50 m in vertical thickness and up to 500 m in strike length. Dark-grey mudstone and pyritic argillite are most commonly associated with slumped and fractured wacke, and are observed to be mixed with undeformed pebble conglomerate. Such lutaceous strata are characteristic of the Sops Head Complex. However, they are absent in the Roberts Arm and Wild Bight groups, and are exceedingly rare in the Badger Group.

Porphyritic, amygdoidal and glomerophyric basalt and dark-grey pillow breccia illustrate primary textures in many localities in the complex. Locally, such basalts are found in depositional contact with volcaniclastic sandstone or, more rarely, with limestone. However, fault-bounded chloritized basalts are more common. In several places, basalts are partially sericitized and silicified and, where orange-brown in colour, contain disseminations and veinlets of pyrite and iron-rich carbonate. Small gabbro bodies intrude the unbroken sequences of volcanic and sedimentary strata in the Sops Head Complex.

Pebbles, cobbles and boulders of epidotized basalt occur as detrital clasts in graded thick-bedded wackes within the Sops Head volcaniclastic successions. They are also present within the complex's massive or poorly stratified debrites. Similar types of sedimentary rocks fill irregular fissures in fractured basalt at the margins of megarafts in the Sops Head melange.

Certain successions of volcanic and carbonate rocks within the Sops Head Complex are demonstrably Middle Ordovician (Nelson, 1981; Clarke, 1992). Whereas some of the shale and siltstone-dominated sequences contain Middle to Late Ordovician graptolites (Clarke, 1992), other mudstone-dominated sequences in the complex are probably older, as they are penecontemporaneous with the bedded volcanic and volcaniclastic strata.

Recent work on the lithogeochemistry of volcanic flows and tuffs in the unbroken formations of the Sops Head Complex indicates that most of the felsic and mafic extrusions are island-arc related (Clarke, 1992). This means that such strata cannot be derived from volcanic-bearing units nearest the complex, such as the MORB tholeiites in the Crescent "terrane" or the alkali basalts and subalkalic tholeiites in the Badger Bay volcanic unit of the Wild Bight Group. Nevertheless, based on regional considerations of this part of the Dunnage Zone, the above-mentioned extrusive rocks are most probably Early to Middle Ordovician.

The presence of island-arc related volcanic rocks in the Sops Head Complex might imply that such strata are completely exotic to the region, though all previous workers have considered the complex's volcanic rocks to belong to either the Roberts Arm or Wild Bight groups. However, if they are correlatable with the arc-related extrusive rocks exposed in the western tracts of the Roberts Arm Group or the eastern tracts of the Wild Bight Group, then one of two alternative possibilities could apply.

The first explanation is that Sops Head volcanic strata comprise parts of allochthonous thrust sheets that had probably travelled in excess of five kilometres. A second interpretation is that island-arc and back-arc sequences in the Roberts Arm map area were already juxtaposed by the Early to Middle Ordovician, so that both were present in the Tommy's Arm area before the development of the Red Indian Line melange.

Broken Formations of the Sops Head Complex

In the area surveyed, mesoscopically broken volcano-sedimentary formations comprise a regionally mappable division of the Sops Head Complex (Figure 2). The largest part of this unit is composed of highly strained, multiple-foliated, rusty-weathering, block-in-matrix melange. North-east of Tommy's Arm River, such rocks appear to be structurally gradational with sequences of interbedded dark-grey shale and light-grey siltstone, which preserve graptolites, primary sedimentological features and a low-angle bedding–cleavage intersection.

Most tracts of block-in-matrix melange in the Sops Head Complex contain internal belts of platey tectonic schist in which a low-grade transposed foliation is readily recognizable in the field. Certain platey schists are mafic in composition and are apparently derived from basalt or gabbro. Other quartzofeldpathic platey schists probably have a sedimentary protolith (relict plutonic cobbles in straightened wacke); some are distinctly carbonaceous or graphitic.

In places, recrystallized wacke with relict sedimentary features display *en echelon* sigmoidal fractures filled with fibrous quartz veins. The steeply dipping fibres within these veins are parallel to the subvertically pitching, dip–slip stretching lineation. Folds of these veins are striated by both vertical and horizontal slickensides.

In the Sops Head Complex, it is evident that some small-scale blocks are porphyroclasts which display strongly asymmetric tails. With increasing bulk strain, these porphyroclasts become progressively comminuted in the highly-foliated, shear-banded argillaceous matrix of the melange. Where porphyroclastic texture is well developed in the Sops Head Complex and the adjacent Roberts Arm Group, relict crenulation cleavage, microfolded veinlets and rootless isoclines of bedding are observable within comminuted lozenges or podiform blocks augened by the matrix foliation. Narrow zones of cataclasite form subparallel to the dip-lineated shape fabric within partially detached lozenges; they contain randomly oriented fragments of a composite schistosity.

All of the regional structures developed in the melange tracts of the Sops Head Complex are Middle to Late Ordovician or younger. However, in low-strain augen, large primary-textured blocks are preserved which contain fossiliferous limestone and basalt, bedded pillow lavas wrapped by unfoliated mudstone, and thixatropically deformed pebbly wacke chaotically injected by pyritic mudstone.

The age of these probable olistostromal melange tracts is equivocal. Some may be Late Ordovician or Early Silurian and possibly be related to the syndepositional intrabasinal tectonism evident in the Badger Group. Others could have formed in the Early to Middle Ordovician and reflect events affecting volcaniclastic strata in the Roberts Arm or Wild Bight groups.

NOTRE DAME SUBZONE

Certain stratigraphic elements of the Roberts Arm Group were inhomogeneously deformed and tectonically incorporated into the Red Indian Line structural zone. Other less-deformed sequences of sedimentary or volcanic strata in the southeastern part of the Roberts Arm Group comprise regionally mappable divisions similar to those observed in the Cottrells Cove Group on the Fortune Harbour peninsula (Dec and Swinden, 1994).

Crescent Lake Formation

The Early or Middle Ordovician Crescent Lake Formation of the Roberts Arm Group is locally composed of three discrete rock units (O'Brien and MacDonald, 1996). The formation consists of a unit of basalt and volcanic breccia, a unit of dominantly red chert having subordinate fine-grained clastic rocks, and a unit of sandy and conglomeratic turbidites.

The mafic volcanic rocks include vesicular dark-grey basalt flows, light-green basaltic agglomerate, and pillow breccia with interstitial red chert. Bostock (1988) assigned all of these rocks to his Crescent "terrane". The distinctive red chert of the Crescent Lake Formation is rhythmically interbedded with grey chert and thin-bedded siliceous argillite, and both are interstratified with medium-bedded, graded, grey and green sandstone. The turbidite-dominated unit contains medium- to thick-bedded, green sandstone having abundant jasper clasts, poorly bedded wacke containing red chert and basalt fragments, and red- or grey polymictic conglomerate containing conspicous volcanic and plutonic boulders.

Internally, each unit of the Crescent Lake Formation contains sections of stratigraphically continuous rocks. In different parts of the area, however, the structurally coherent parts of a particular unit commonly display opposing stratigraphic-facing directions. Moreover, due to competancy contrasts, the unit boundaries are typically faulted. As a result, in the small portion of the "Crescent terrane" surveyed for this project, the original stratigraphic order of the Crescent Lake Formation could not be unequivocally discerned.

In this regard, the order of superposition of volcanic and sedimentary rocks in the Moores Cove Formation of the Cottrells Cove Group (Dec and Swinden, 1994) may provide a reasonable framework for stratigraphic analysis of the Crescent Lake Formation. Accordingly, in the area of Tommy's Arm River, the Ordovician depositional order of map units may possibly have been basal tholeiite succeeded by chert followed by turbidite. The regional disposition and facing directions of the sedimentary divisions, together with the nature of their epiclastic detritus, support the contention of original tholeiite-cored anticlines and turbidite-cored synclines in the Crescent Lake Formation.

In the vicinity of the Red Indian Line, a tectonic stack of fault-bounded rock panels each contain a lithological unit of the Crescent Lake Formation. Truncated obliquely along their strike, these come in direct contact with the Badger Group, the Shoal Arm Formation, the Wild Bight Group and the Sops Head Complex (Figure 2). Elsewhere in the map area, where Crescent Lake units are less attenuated but also duplicated, the total tectonic thickness of the formation is estimated to be about 1.5 km thick.

PRETECTONIC INTRUSIVE ROCKS

Hypabyssal Intrusions

In the map area, small thrust-faulted sills of gabbro–diorite and highly sheared diabase dykes occur, in places, within the Roberts Arm Group. Some of these hypabyssal intrusions have been interpreted by Bostock (1988) as subvolcanic in origin on the basis of their geochemical similarity with the Crescent Lake basalts. These minor intrusions cannot be represented on 1:50 000-scale geological maps of the region (e.g., the Rust Pond–Ghost Pond showing; Evans, 1996).

The deformed mafic intrusions found in the Badger Group and the Sops Head Complex are, in general, less common and much smaller than those in the Roberts Arm and Wild Bight groups. Some of these dykes and sills are probably Silurian. In the Bay of Exploits region of the Exploits Subzone, Badger Group-hosted mafic intrusions have been postulated as pretectonic feeders to Silurian terrestrial volcanic rocks (Kusky, 1985).

STRUCTURE

In the area surveyed, the regional distribution of Exploits Subzone rocks is essentially controlled by northwest-trending folds and related bedding-parallel thrust faults. These primary structures are responsible for placing the Wild Bight Group above the Shoal Arm Formation or younger stratigraphic units. East of Rocky Pond, early formed thrusts associated with a gently northeast-dipping foliation are interpreted to have imbricated the Roberts Arm Group with the Gull Island Formation (Figure 2).

PRIMARY STRUCTURES

Primary thrust and reverse faults developed preferentially on the highly strained limbs of coeval major folds. In essence, the primary regional structures comprise a small thrust-and-nappe belt in the area surveyed.

From detailed mapping, it seems that thrusts cut through the rock sequence on the overturned limbs of folds at a very low angle, though this is rarely observed on exposure scale. Locally, however, limb thrusts ramp upward and obliquely cross the axial surface of the primary folds (Figure 2).

Approaching ductile faults that bound a particular folded panel of stratified rocks, periclinal folds within the nappe change from being upright to being inclined in the dip direction of the adjacent thrust. This upright-recumbent transition is typical of low-grade thrust belts controlled by underlying low-angle contractional shear zones.

In the western part of the map area, ductile reverse faults define the northeast and southwest margins of the Wild Bight Group (Figure 2). In certain localities, offset along these primary regional structures caused the complete tectonic excision of the other regional lithostratigraphic units of the Exploits Subzone. At the same time, in other locations along the tectonized periphery of the Wild Bight Group, certain stratigraphic intervals of the Shoal Arm and Pennys Brook formations were structurally repeated by thrust imbrication. Although the relative ages of the primary boundary thrusts are conjectural, inverted sequences of overplated Wild Bight Group rocks occur in the hanging wall of both the northeast- and southwest-dipping faults.

Minor primary structures are present near reverse faults in many of the hanging wall and footwall sequences in the area mapped. These include tight to isoclinal minor folds, well-developed cleavage or other platey foliations, and strong down-dip stretching lineations.

INTERFERENCE PATTERNS

The primary tectonic structures observed in the Sops Head Complex, Wild Bight Group, Shoal Arm and Gull Island formations were overprinted by northeast-trending regional folds, slaty cleavage and associated reverse faults. These secondary features are the most widely developed structures in the area between Tommy's Arm River and Shoal Arm Brook (Figure 2). The thrust stack of the Roberts Arm Group northwest of the Red Indian Line melange appears to have formed contemporaneously with the secondary structures in the Exploits Subzone.

Between North Twin Lake and Sops Lake, primary tectonic features are well-preserved in the complex structural dome noted by previous workers. However, westward and eastward, northwest-trending primary structures have been reoriented and variably reworked. There, secondary fault zones have displaced primary structures (Figures 2 and 3). Examples include a major refolded anticline in the Wild Bight Group and a major refolded syncline in the Badger Group. The dominant plunge direction of the secondary folds is northeastward; whereas, the primary folds plunge regionally northwestward.

The map-scale secondary folds between Tommy's Arm River and Sops Arm Brook are S-shaped when viewed down-plunge (Figures 2 and 3). In this area, the strike of certain primary structures can be mapped to swing continuously from the short middle limb to the northeast-trending long limb of the S-folds. This means that many primary folds and thrusts can be viewed in a vertical northwest–southeast section. Moreover, the geometry of the primary structures would be approximately the same as that seen in a northeast–southwest cross section, especially where strain related to secondary deformation is low.

In the regional composite section illustrated in Figure 3, primary faults that were originally gently northeast dipping (those which bound the largest body of Sops Head melange) dip away from the viewer. The faults are shown looking down-the-pitch of the stretching lineation. The overlying fold nappe in the Wild Bight Group is illustrated in an oblique down-plunge section, but one reasonably close to the profile plane of the anticline adjacent to the boundary thrust.

Primary faults that were originally southwest-dipping (those which place the Wild Bight Group structurally above the Gull Island Formation) dip toward the viewer. However, they cannot be accurately represented in this two-dimensional section. Designated by asterisks, these are shown in their reoriented position, inclined northwestward on the inverted limbs of secondary sinistral folds (northeast-trending S-shaped folds).

SECONDARY STRUCTURES

Secondary folds are asymmetric and tight in the footwall and hanging wall sequences of secondary reverse faults. However, they are observed to be concentric and open in stratigraphically continuous sections within the larger thrust-faulted panels of stratified rocks (e.g., the fault-bounded anticlinorium between Sops Arm and Shoal Arm brooks; Figure 3). The plunge of secondary folds varies from gentle to steep. It is largely dependent upon whether the smaller scale secondary folds formed in the hinge zone of the over-printed primary folds, or on the right-way-up or overturned fold limbs.

Secondary folds were developed on the northwest limb of the major northeast-plunging anticline exposed near Shoal Arm Brook. They have an asymmetry consistent with the presence of an upward-facing synform located farther north-west. Strata are variably gently and steeply dipping on this fold limb but face regionally northwestward (Figure 3).

In contrast, secondary fold trains between Tommy's Arm River and Sops Arm Brook have antiforms located southeast of synforms, and most stratigraphic sequences in this area face regionally southeastward (Figure 3). Like the fold structures near Shoal Arm Brook, these antiform–synform pairs are, for the most part, upward facing and northeast plunging. Thus, a regional structural and stratigraphic-facing

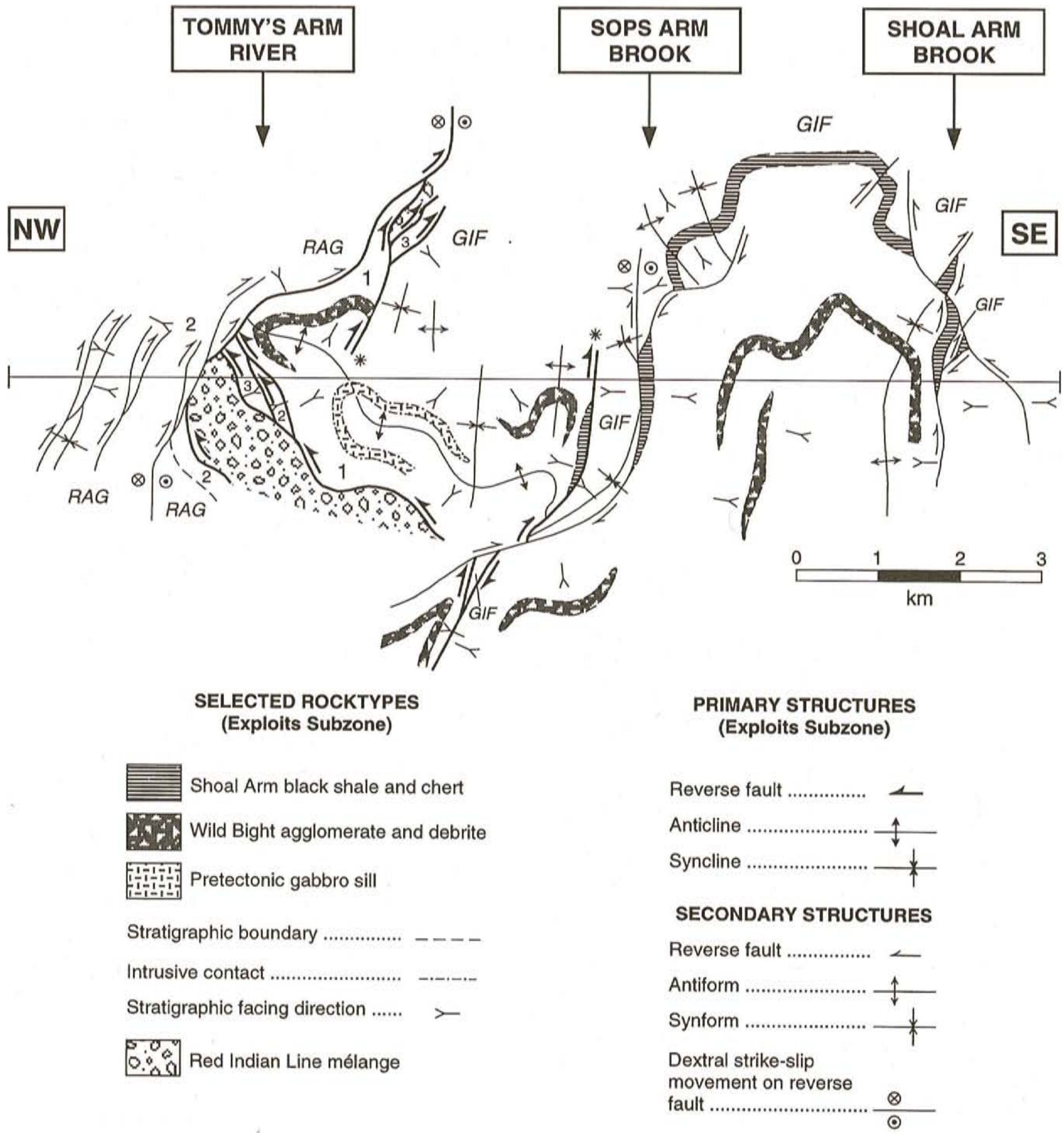

Figure 3. *Regional cross section illustrating some of the major structures of the Tommy's Arm River–Shoal Arm Brook area as outlined by selected rock units. Faults marked by asterisks are the same feature, however they cannot be accurately shown as a continuous structure in one cross section only. The relations of the fault as seen in different NW-SE sections have been projected onto the composite cross section illustrated. RAG and GIF indicate Roberts Arm Group and Gull Island Formation, respectively.*

confrontation must occur in the vicinity of Sops Arm Brook. Though a major secondary syncline is predicted, this area is instead marked by the largest secondary fault zone in the Exploits Subzone.

Offset along the Sops Arm Brook fault is interpreted to have had both a vertical and horizontal displacement vector. A pure strike-slip or subhorizontal oblique component of movement affected this ductile zone of secondary reverse faulting. In the footwall sequence beneath the northwest-dipping overthrust, bedding-parallel lateral movement is recorded by steeply plunging drag folds of the regional foliation. There, in a right-way-up succession of northwest-dipping rocks, steep slaty cleavage is northwest striking in relatively competent wackes and north striking in relatively incompetent argillites. The differential displacement of foliation across bedding planes gives rise to the Z-shape of megascopic drag folds of the slaty cleavage.

The dextral offset of foliation surfaces is an indicator of the sense of external rotation governing the transcurrent strike-slip or gently oblique-slip shear zones. Evidence is also provided by cleavage lithons, many of which display clockwise-rotated asymmetric tails in plan view. The principal shear planes of these right-handed shear zones are bedding planes; locally, they are represented by the lower and upper surfaces of individual beds. Accordingly, deformation related to dextral shearing produced systematic variations in the trend of the original bedding–cleavage intersection lineation.

The sense of internal rotation within secondary dextral shear zones is provided by the sinistral vergence of tight to isoclinal S-shaped folds. Inhomogeneously developed, these are present in highly attenuated, well-cleaved argillite beds. In contrast, open M-shaped crenulation folds of slaty cleavage are located in adjacent wackes.

In the map area, the largest incremental strain produced during dextral oblique-slip faulting is observed within the Sops Head Complex. Though focussed along the Red Indian Line, this type of deformation is assumed to be coeval with that recorded farther east, i.e., the shearing seen adjacent to northwest-dipping reverse faults within the Wild Bight Group. Regardless, throughout the region, rocks in the hanging wall of northwest-dipping thrusts have moved upward and northward, while the underplated footwall sequence moved southward.

Regional Setting of Bivergent Reverse Faults

In the Sops Lake–Sops Arm Brook area, the Shoal Arm and Gull Island formations display northwesterly overturned as well as upright secondary folds (Figure 2). The overturned asymmetric folds are thought to have been generated over a ramp in the northwest-dipping Sops Arm Brook fault (Figure 3). Alternatively, they may be reoriented primary folds.

Farther southeast, in the Shoal Arm Brook area, northwest-dipping secondary faults form small schuppen zones composed of alternating Middle and Late Ordovician strata (Figures 2 and 3). Here, however, the northwest-dipping imbricate fault zone is crosscut by a secondary reverse fault that dips steeply southeastward. The youngest reverse fault juxtaposes a northwest-facing panel of the Wild Bight Group to the east against a southeast-facing panel of the Wild Bight Group to the west. On regional grounds, it places older strata above younger strata.

These secondary faults are similar in regional orientation to primary reverse faults that have been reoriented from their initial northeast inclination by superimposed secondary folds. However, features that originally dipped southeastward (southeast-over-northwest thrusts) formed much later in the structural history of the map area. Most of the regional northeast-trending thrusts and reverse faults in the New Bay–Bay of Exploits region are southeast dipping, and these become increasingly dominant progressing eastward across Notre Dame Bay.

SYNTHESIS AND IMPLICATIONS

The effect of the primary regional structures was to significantly modify the stratigraphic succession of low-grade rocks in the Tommy's Arm River–Shoal Arm Brook area. As a consequence of this period of deformation, map unit contacts are more commonly observed to be faults than original stratigraphic boundaries.

The disposition of major rock units by primary structures is schematically illustrated in a northeast–southwest cross section of the western part of the region (Figure 4a). The relative arrangement of units is that hypothesized to have occurred at the end of the early stage of regional deformation.

Disposition of Units by Primary Structures

The anticlinal nappe cored by the Wild Bight Group is thought to have been originally transported southwestward, as most of the Pennys Brook Formation has been excised along the northeast-dipping thrust bounding this fold nappe. Near North Twin Lake, the large-strain deformation seen in the Sops Head Complex, coupled with the numerous thrust faults recorded in the adjacent Crescent Lake Formation of the Roberts Arm Group, may indicate footwall collapse beneath the overriding nappe.

Crosscutting relationships between primary thrusts have been mapped in the Tommy's Arm River–Sops Lake area (Figure 2). Regionally, the northeast-directed primary struc-

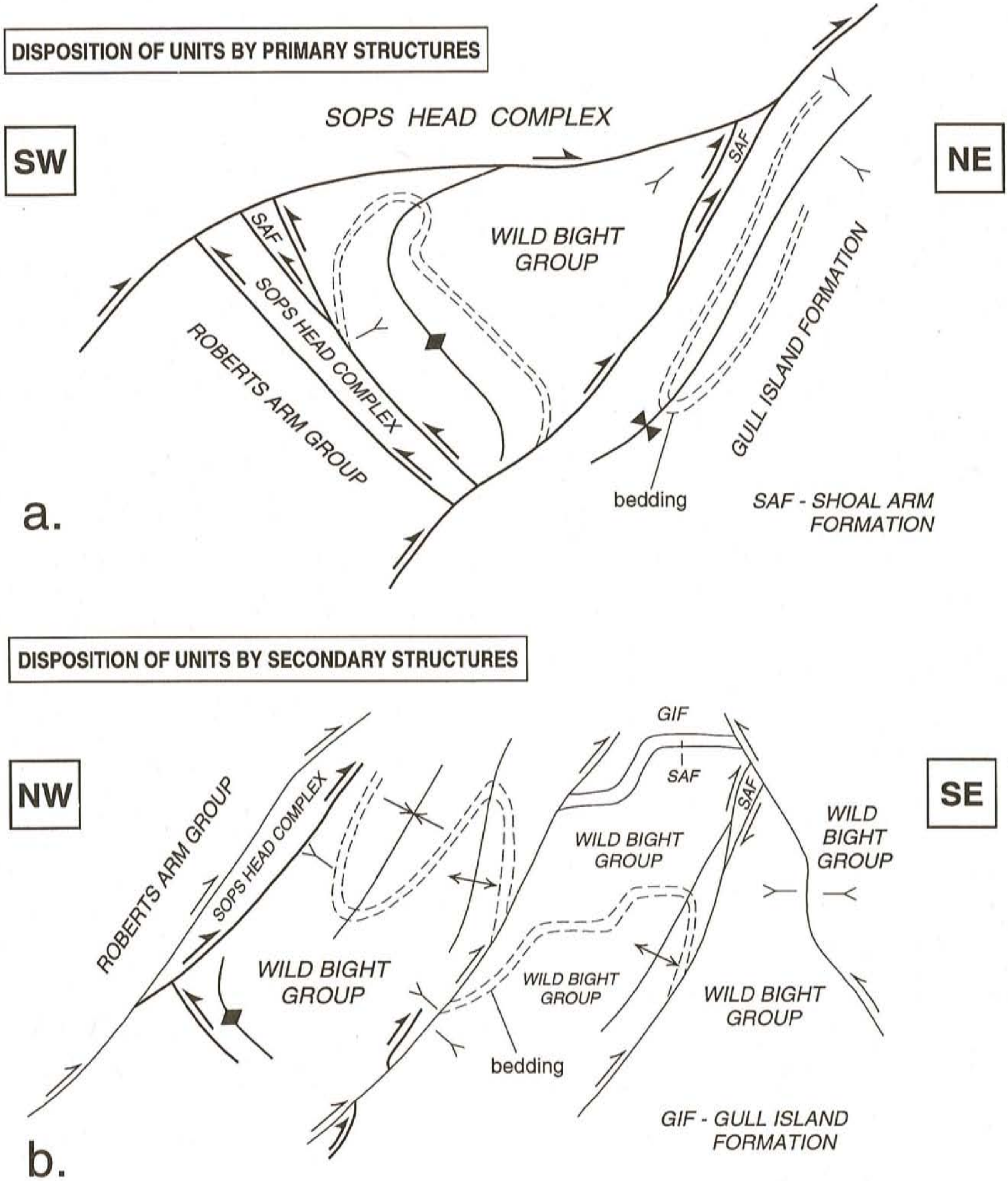

Figure 4. *Schematic cross sections depicting northwest-trending primary and northeast-trending secondary structures, and portraying their control over the disposition of rock groups in the area surveyed. Symbols as for Figure 3.*

tures are assumed to have postdated the southwest-directed primary structures, as the former produced lower-magnitude bulk strains and resulted in comparatively lesser amounts of stratigraphic separation. Therefore, it is the younger southwest-dipping faults that may have caused the uplift and partial detachment of the Wild Bight Group nappe (the purported pop-up structure depicted in Figure 4a). They may also have truncated and structurally isolated the ductile fault zone that originally separated the Sops Head Complex from the Roberts Arm Group.

In the northwestern part of the map area, the Sops Head Complex is observed to occur in the hanging wall of what are interpreted to be the younger set of northeast-directed primary thrusts (Figure 2). This contrasts with relationships seen in the southwestern part of the area, where the Sops Head Complex is seen in the footwall of the older southwest-directed thrusts. The pop-up structure in the Wild Bight Group is interpreted to have been overridden by the Sops Head Complex (Figure 4a). The complex's melange unit lies above a southwest-dipping fault that might represent the roof thrust of a primary duplex. In this explanation, the Wild Bight Group would terminate northwestward in a narrow horse, tectonically separated from the main part of this rock group.

Disposition of Units by Secondary Structures

The second period of regional deformation caused a more widespread disruption of the lithostratigraphic successions and further complicated the distribution of the map units. Secondary structures rearranged previously assembled lithotectonic sequences.

The disposition of stratigraphic units by secondary structures is schematically illustrated in a northwest–southeast cross section of the entire map area (Figure 4b). Most of the map-scale folds and faults surveyed in the region between Tommy's Arm River and Shoal Arm Brook developed at this time, especially those in the Exploits Subzone. The Wild Bight Group is disposed in three major northeast-trending thrust sheets, each of which are bounded by northwest-dipping secondary reverse faults (Figure 4b). Strata within each tectonic panel are folded about secondary folds having upright and inclined axial surfaces. At least one of the folds having an inclined axial surface is crosscut by a secondary reverse fault.

Various stratigraphic levels of the Pennys Brook Formation are exposed in each of the thrust sheets. Rocks become generally younger in opposing directions in tectonically adjacent panels of southeasterly overthrusted rocks. In the Wild Bight Group, the northwestern panel faces southeastward, the central panel faces northwestward, and southeastern panel faces southeastward (Figure 4b). It appears that the Shoal Arm Formation is an important detachment horizon for primary and secondary reverse faults in the Exploits Subzone (Figure 3).

A structural-facing confrontation, associated with the development of bivergent secondary thrust faults, occurs in the eastern part of the map area. There, older rocks in the eastern part of the Wild Bight Group probably overthrust, along southeast-dipping faults, the southeast-directed imbricate thrust sheets developed in the western part of the Wild Bight Group.

Secondary northwest-dipping reverse faults displaced and reactivated primary reverse faults on the overturned limbs of secondary folds (Figure 4b). This occurred most commonly in the west of the map area and is particularly evident in the Red Indian Line structural zone. Here, a thrust stack containing the various divisions of the Crescent Lake Formation was emplaced along a northwest-over-southeast oblique reverse fault. In most places, this structure forms the southeastern boundary fault of the Roberts Arm Group. It may have utilized primary thrusts in the Sops Head Complex or the roof thrust of the primary duplex discussed above (Figure 4b). The tectonic panel of the Roberts Arm Group that now structurally overlies the Wild Bight Group (or other Exploits Subzone units) may have possibly been rooted in a part of the group that originally underplated the Wild Bight fold nappe.

One economic implication of the regional structural relationships discussed in this paper concerns the early stage fold nappe recently identified in the volcaniclastic sedimentary units of the Roberts Arm Group near the Gullbridge massive sulphide deposit (Calon and Pope, 1990; Pope *et al.*, 1991). Now southeastward-closing as a result of superimposed deformation (Pudifin, 1993), this thrust-bounded subrecumbent fold may structurally underlie the larger of the two fault panels of Red Indian Line melange depicted in Figure 3. In the map area, as elsewhere in the Buchans–Roberts Arm–Cottrells Cove belt, the vertical structural sequence of rocks is a completely unreliable indicator of the depositional order of groups and formations found in the Exploits and Notre Dame subzones. This has led to a protracted debate about the broken and unbroken formations of the Sops Head Complex and the presence of the Red Indian Line near Badger Bay.

POSTTECTONIC INTRUSIVE ROCKS

In the southwestern part of the area surveyed, intrusions previously included in the Twin Lakes Diorite Complex display map patterns suggesting their emplacement into stratified rocks of the Notre Dame Subzone (Figure 2). The largest part of this igneous complex, however, is situated within the Exploits Subzone.

Near Rocky Pond, unfoliated granitic rocks crosscut large second-stage structures that are present in the Roberts Arm and Badger groups (Figure 2). Eastward, on North Twin Lake, the contact of a granodiorite–diorite pluton traverses the primary imbricate thrust stack of the Red Indian Line structural zone.

TWIN LAKES DIORITE COMPLEX

A variety of plutonic rocks of mafic to intermediate composition occur within Dean's (1977) Twin Lakes Diorite Complex. In places, they are intruded by minor granite sheets, small aplite dykes and rare diabase. Some of the main rock types in the igneous complex are i) coarse-grained, hornblende-bearing, heterogeneous, dark-grey diorite having mafic inclusions and schlieren-textured pegmatite segregations, ii) equigranular, medium- to fine-grained, homogeneous, dark-grey diorite having secondary epidote and chlorite, and iii) massive, medium-grained, biotite-bearing, leucocratic granodiorite.

Most of these intrusive rocks are probably Siluro-Devonian in age. Immediately southwest of the map area, one of the diorite phases in the complex is isotopically dated as Llandovery (G.R. Dunning, unpublished data, *in* Pope *et al.*, 1991). In the vicinity of Great Gull Lake (Figure 1), this diorite is apparently intruded by a body of granodiorite that crosscuts the Red Indian Line near the Gullbridge deposit (Pudifin, 1993). Southeastward, in the Frozen Ocean Lake area (Figure 1), Kusky (1985) described similar intrusions as postdating several phases of ductile deformation in the Badger Group, and to have had been emplaced into several of the originally southwest-directed thrust sheets in that region. In this same general area, Swinden (1988) demonstrated that some of the high-level granites intruded flow-banded rhyolites belonging to the Silurian Charles Lake Volcanics.

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